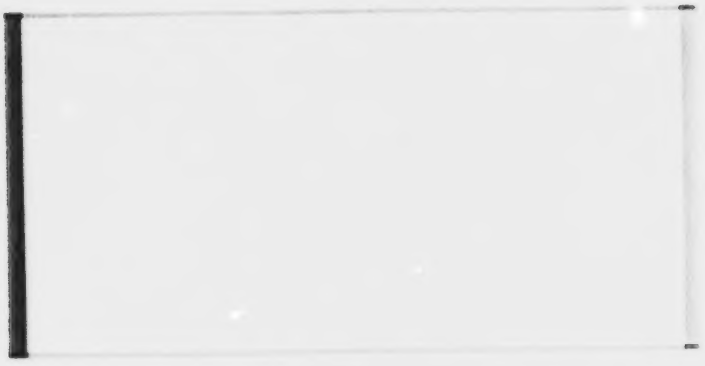
Ontario Hydro



RESEARCH DIVISION

91602
new 82-10

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part.

ontario hydro
research division

ULTRASONIC SHEAR WAVE CHARACTERIZATION OF CANDIDATE USED FUEL CONTAINER MATERIALS

Report No 86-72-K

M.D.C. Moles
Engineer-NDE
Nondestructive & Fracture Evaluation Section
E.A. Ginzel and R.K. Ginzel
Ginzel Brothers and Associates

ABSTRACT

Nuclear used fuel containers require remote closure before final disposal. Most current container concepts involve welding and remote ultrasonic inspection. Candidate container weld materials (copper, titanium grades 2 and 12, stainless steel 316, Inconel 625, Hastelloy C-276) were examined using shear waves to determine ultrasonic anisotropy, in particular beam skewing. Four characterization techniques were developed for evaluating the weld specimens, of which the immersion cylinder technique was the most repeatable. The results showed that the titanium grade 2 was highly isotropic, the titanium grade 12 was fairly isotropic, but that the copper, Inconel, Hastelloy and stainless all showed severe anisotropy with shear waves.

job	file	date	report no
740683-261-401	826	July 7, 1986	86-72-K

91602
new 82-10

ontario hydro
research division

EXECUTIVE SUMMARY

ULTRASONIC SHEAR WAVE CHARACTERIZATION OF CANDIDATE USED FUEL CONTAINER MATERIALS

M.D.C. Moles, Metallurgical Research Department
E.A. Ginzel and R.K. Ginzel, Ginzel Brothers and Associates

Most container designs for the long term underground isolation of nuclear used fuels include a final closure weld for sealing the container. These welds must be remotely inspected before disposal, and ultrasonics has been selected as the most suitable technique. Due to known or possible problems, such as beam skewing, it is necessary to ultrasonically characterize potential container materials. Weld cylinders and rectangles were made from stainless steel 316, copper, titanium grades 2 and 12, Inconel 625, Hastelloy C-276, plus mild steel and pyrex reference cylinders. Four characterization techniques were developed, and of these, the immersion cylinder technique gave the most repeatable results. The results showed that titanium grade 2 was highly isotropic, titanium grade 12 was fairly isotropic, but the copper, Inconel, Hastelloy and stainless showed severe beam skewing. While further characterization of these welds is recommended, eg, to determine frequency effects, it is also recommended that the large US BWR program on inspection of centrifugally cast stainless steel be monitored for future developments.

JAB
9/B

job	file	date	report no.
740683-261-401	826	July 7, 1986	86-72-K

TABLE OF CONTENTS

		PAGE
1.0	BACKGROUND	1
2.0	ULTRASONIC RESEARCH ON ANISOTROPIC METALS	2
3.0	EXPERIMENTAL PROCEDURES	4
3.1	Immersion Technique for Cylinders	4
3.2	Immersion Technique for Rectangles	5
3.3	Contact Technique for Rectangles	5
3.4	Contact Technique for Cylinders	5
4.0	EXPERIMENTAL RESULTS	6
4.1	Results from Immersion Tests on Cylinders	6
4.2	Results from Immersion Rectangle Tests	6
4.3	Results from the Contact Rectangle Technique	6
4.4	Results from the Contact Cylinder Tests	7
5.0	DISCUSSION	7
5.1	Evaluation of the Techniques	7
5.2	Implications of the Results	8
6.0	CONCLUSIONS	9
7.0	RECOMMENDATIONS	9
	REFERENCES	11
	TABLES	13
	FIGURES	14
	DISTRIBUTION	last page

LIST OF TABLES

TABLE 1 - Sample Beam Skewing Results from Immersion Cylinder Tests

TABLE 2 - Beam Skewing from Immersion Test on Rectangles

LIST OF FIGURES

FIGURE 1 - Weld Layout and Specimen Preparation

FIGURE 2 - Generation of Shear Waves in Specimens

FIGURE 3 - Equipment Setup for Generating SV Waves Using Immersion Cylinder Technique

FIGURE 4 - Schematic of Immersion Rectangle Technique Set-Up

FIGURE 5 - Schematic Showing Contact Rectangle Technique Using Two Polarized, Shear Wave Probes

FIGURE 6 - Schematic Illustrating Contact Cylinder Technique

FIGURE 7 - Immersion Cylinder Isometrics:

7a - mild steel; 7b - titanium grade 2;
7c - titanium grade 12 LT;
7d - titanium grade 12 HT; 7e - stainless steel;
7f - copper LT; 7g - copper HT;
7h - Inconel LT; 7i - Hastelloy LT;
7l - pyrex; 7m - mild steel longitudinal wave;
7n - vertical displacement profiles for mild steel;
7o - vertical displacement profiles for titanium grade 2.

FIGURE 8 - Immersion Rectangle Scans

8a - mild steel;
8b - copper LT.

FIGURE 9 - Contact Cylinder Isometrics

9a - mild steel;
9b - titanium grade 2;
9c - titanium grade 12 HT;
9d - Hastelloy HT.

91601
new 82-10

ontario hydro
research division

To

Mr. H.N. Isaac
Manager
Nuclear Materials Management
H10A27

ULTRASONIC SHEAR WAVE CHARACTERIZATION OF CANADIDATE USED FUEL CONTAINER MATERIALS

M.D.C. Moles[1], E.A. Ginzel[2] and R.K. Ginzel[2]

1 Ontario Hydro Research Division
2 Ginzel Brothers and Associates, Waterloo, Ontario

1.0 BACKGROUND

The current Canadian concept of disposal of used fuel from CANDU nuclear reactors is to isolate the fuel in corrosion-resistant containers, and to place these containers at a depth of 500 to 1000 m in plutonic rock. As part of its Technical Assistance Program within the Nuclear Fuel Waste Management Program of Atomic Energy of Canada Limited, Ontario Hydro is performing containment and immobilization studies. Although several container designs are under consideration, most consist of a metal container with welded-on lid. Part of the Technical Assistance Program involves developing remote nondestructive evaluation (NDE) techniques to ensure the mechanical integrity of the final closure weld, and that a sufficient corrosion barrier exists. Ultrasonics has been established as the most suitable NDE technique. However, some of the candidate materials were known to exhibit severe ultrasonic beam skewing due to the formation of large anisotropic grains during welding, while other materials were uncharacterized. The objective during this Concept Assessment phase was to characterize this beam skewing and to identify any other NDE problems in the candidate container materials/1/.

As part of the Canadian Container Development Program for Fuel Isolation/2/, a number of materials have been selected as possible candidates for used fuel containers, primarily on the strength of their corrosion resistance. These materials are:

1. 316L stainless steel
2. Titanium grade 2
3. Titanium grade 12
4. Commercially pure copper
5. Inconel 625
6. Hastelloy C-276.

Thick-section welds of these materials were manufactured and cylinders and small rectangular blocks of weld material prepared, plus a mild steel rod and weld and a pyrex rod for reference. These cylinders and rectangles were examined ultrasonically using shear waves to determine the extent of beam skewing (see section 3.0). Previous work using longitudinal ultrasonic waves on these weld cylinders had indicated that the mild steel and titanium welds showed little beam skewing, while the stainless, Inconel, Hastelloy and copper all showed severe beam skewing /3/. The previous work also indicated that the most important symptom of the anisotropy was beam skewing, rather than changes in beam width or number of peaks.

The objective of this work on ultrasonic shear wave behaviour in candidate weld materials was similar to the work on longitudinal waves, namely to rank the welds in terms of their ultrasonic inspectability. In practice, most ultrasonic inspections of welds use shear waves, though it is more difficult to assess the effects of anisotropy this way for practical reasons. It should be noted that most other researchers have been primarily interested in either characterizing the phenomena of beam skewing or improving the inspectability of specific materials (see Section 2.0 below).

2.0 ULTRASONIC RESEARCH ON ANISOTROPIC METALS

A considerable amount of work has been performed by other workers on characterizing the ultrasonic behaviour of austenitic-type welds from several different aspects/4-20/. Most of the work has been performed on 300 series stainless steels, with the balance on Inconel 82, which is also used for reactor vessel cladding. This work has ranged from theoretical and experimental analysis to modelling beam skewing to developing techniques for improving inspectability.

Kupperman et al/9-11,18/, Tomlinson et al/20/. and Adler et al/5,7/ have shown that austenitic welds typically consist of large grains growing with their <001> direction in the z-plane (see figure 1), with fairly random x and y orientations. In contrast to ferritic steels, no phase transformations occur in austenitic steels on cooling, so no recrystallization, and hence randomization, of the microstructure occurs. Thus, the austenitic-type weld microstructures consist of very long, oriented grains in the z (out of weld plane) direction. This can have three effects/9/: (1) ultrasonic attenuation increases due to grain boundary scattering, though this would not be a major problem for thin-walled containers; (2) mode conversions can occur;

and (3), most important for nuclear waste containers, beam steering/skewing occurs because ultrasonic beams are diffracted by changes in velocity between grains of different orientations.

Crystallographic-type studies/5,7,9-11,18,20/ have shown that ultrasonic velocity (and hence beam skewing) can be fairly satisfactorily correlated with single-crystal elastic constants and with resulting theoretical models, given the expected variation between welds. Kupperman et al in particular/11/ have shown that longitudinal waves can expect a beam skewing of up to 21° at certain orientations in stainless steels, while shear waves polarized in the vertical direction (SV) can undergo skewing up to 44°, and SH waves (horizontally polarized shear waves) up to 13°. Longitudinal waves are least affected at a 45° refracted angle (relative to the z-axis), while SV waves are worst at around 45° to 60° refracted angles/7,10/. Unfortunately, most ultrasonic inspections use 45°-60° angles with shear waves, since for many welds the weld z-axis is perpendicular to the inspection surface.

A beam skewing model has been developed by Silk/15/, using a finite element-type mesh to model the changes in velocity and other physical properties in anisotropic welds. Kupperman et al/11/ have developed a model for predicting beam skewing, which correlates reasonably with experimental results.

Other workers have attempted to improve inspectability by signal processing or other means. Mech et al/6/ and Dau/4/ have investigated adaptive learning techniques for improving characterization of defects, with some success. Murali and Neelakantan/16/ have developed a manual spatial signal-averaging technique to improve signal-to-noise ratio, while Kupperman et al/12/ have developed a special purpose computer-controlled jig for a similar purpose. Spatial signal averaging techniques are likely to be particularly applicable to large grained, and hence "noisy" microstructures. Alternatively, a number of workers have pointed out that fine-grained welds typically should be more easily inspected than coarse-grained welds/10,19/.

Caussin et al/13/ have shown experimentally that results vary considerably with welding technique and with the individual welds. In contrast, Edelmann/14/ recommends extensive use of reference blocks to establish reproducible standards. Singh/21/, inspecting extruded pipes with side-drilled holes which also showed ultrasonic anisotropy, has developed a double inspection technique to compensate for expected variations in ultrasonic properties. The first inspection uses shear-waves in pitch-catch, essentially to characterize the material, while the second inspection uses longitudinal waves in pulse-echo to characterize defects. Heinrich et al/17/ recommend the use of specific equipment such as 70° longitudinal wave twin probes. Lott and Malik/19/ have shown that hot-isostatic pressing significantly randomizes microstucture and other benefits and hence improves inspectability, whereas heat treatment has little effect.

3.0 EXPERIMENTAL PROCEDURES

Cylinders and rectangles composed entirely of weld metal were machined from the thick section welds, as shown in Figure 1 /3/. These cylinders or rectangles were inspected using ultrasonic shear waves both in immersion and contact modes (see below). For the cylinders, it was possible to "map" each weld by rotating the cylinder as well as scanning with a receiver probe. With the rectangles, only limited data was obtainable. All four techniques used both separate pulser and receiver probes. These techniques were developed in a previous contract /22/.

3.1 Immersion Technique for Cylinders

This is a modification of the longitudinal wave technique /3/, and uses both pulser and receiver probes angled to generate shear waves only. In all cases, incident angles were selected to give refracted angles about ten degrees greater than the first critical angle. For the Hastelloy, whose shear wave velocity was not available from the literature, it was necessary to measure the velocity using the practical set-up. Figure 2 shows the experimental set-up used to generate the shear waves in the cylinders. This procedure generated SV waves (shear waves polarized in the vertical plane), which is the usual inspection situation. The pulser probe's position was selected using the computer ray-tracing program UT-PATH to generate an approximately parallel sound path within the cylinder. A Krautkramer USIP 11 ultrasonic flaw detector was gated to transmit and receive the signals over an appropriate time range. A focussed 2.25 MHz, 12 mm diameter, 62 mm focal length probe was used as pulser, and an unfocussed 2.25 MHz 12 mm diameter probe as receiver.

Figure 3 shows the complete experimental set-up, consisting of a stepping motor driven rotating turntable holding a water bath and fixturing, a stepping motor driver, an ultrasonic flaw detector to generate and receive pulses, and an Apple computer to drive the turntable and record data. In each scan, the turntable holding the cylinder and pulser probe was rotated 180 degrees, while the receiver probe remained stationary. The pulser and receiver probes were in line after 90 degrees. After each scan, the cylinder was rotated 10 degrees and the scan repeated. After 36 scans a complete ultrasonic isometric of the cylinder was obtained giving received signal amplitude as a function of cylinder position and rotational position. The results were printed out as composite isometrics (see Figure 7). The plots were analysed for beam skew, plot width and number of peaks, as before /3/.

The shear wave tests were different from the longitudinal tests in that significant beam skewing was also observed in the vertical plane (along the cylinder axis). The final technique involved optimizing the signal for the more isotropic signals eg mild steel, and performing a scan at one level only. For the anisotropic materials eg. stainless steel, the technique involved optimizing the signal amplitude in one vertical position, then performing five scans, two above and two below the optimized location, to detect any severe vertical plane beam skewing.

3.2 Immersion Technique for Rectangles

As above, SV waves were generated by using angled transducers (see Figure 4). The rectangles were placed in a water bath, and the pulser and receiver probes scanned along them to generate a deviation from the "ideal" (mild steel). Due to the small size of the rectangles, only the largest face (19 x 25 mm) could be scanned. While this technique could generate information on both horizontal and vertical beam skewing, the results were very limited. The tests were also performed on parent plate rectangles of the candidate materials for comparison.

3.3 Contact Technique for Rectangles

Initially six normal beam, 12 mm active element, shear wave contact probes were purchased, two each of 1, 2.25 and 5 MHz frequency. Coupling with normal beam shear waves requires a non-Newtonian viscous fluid such as honey. Both honey and a special couplant supplied by the probe manufacturer were used. The contact tests on rectangles were performed on the 19 x 25 mm surfaces alone since only these provided sufficient area. Scans were performed using a similar approach to the immersion cylinders to measure amplitude profiles. Figure 5 shows the experimental set up. The scan results were not as consistent as desired due to problems with the coupling, as expected.

3.4 Contact Technique for Cylinders

The contact technique for cylinders was similar to the original longitudinal wave technique /3/, except the shear wave probes were coupled to the cylinders with plastic shoes. Initially curved shoes were used, but these distorted the beam excessively. The receiver probe was scanned round the cylinder in an arc of 120 degrees as before, and the amplitude profile recorded. The cylinder was rotated through 10 degrees and the scan repeated. A 360 degree isometric profile of each weld was built up as before. The experimental arrangement is shown in Figure 6. This technique had difficulty in producing repeatable results due to the problems in maintaining constant coupling. In particular, measuring beam width was not feasible.

4.0 EXPERIMENTAL RESULTS

4.1 Results from Immersion Tests on Cylinders

The isometric plots from the immersion scans on the cylinders are shown in Figures 7a-7k, all taken at the middle scan position. Figure 7l shows a shear wave isometric from the pyrex rod, and Figure 7m a longitudinal wave isometric from the mild steel rod from /3/. Comparisons of Figures 7a and 7m indicate that there is more distortion using the shear wave technique than with the longitudinal wave technique, which is to be expected due to beam refraction. This indicates greater experimental scatter in the shear wave results. Figures 7n and 7o show sample scans for the five vertical positions on various isotropic materials, which give some idea of the amount of variation in the vertical plane.

The isometric in Figure 7b indicates that titanium grade 2 is highly isotropic, as expected. However, figures 7c and 7d show that titanium grade 12 is somewhat less isotropic and shows distinct amplitude trends. This agrees with the longitudinal wave results, though the extent was not so severe with longitudinal waves. Figure 7e shows that stainless steel exhibits severe beam skewing, as expected. Copper, in Figures 7f and 7g, shows almost random beam skewing, as does one of the Hastelloy cylinders in Figure 7k. The Inconel cylinders and the other Hastelloy cylinder in Figures 7h-j show severe beam skewing.

The mean and standard deviation of the beam skew angles for all the cylinders from the isometrics, the mean and standard deviations of the plot widths, and the weighted average numbers of peaks are shown in Table 1. The beam skew, plot widths and numbers of peaks were measured according to techniques developed in /3/.

4.2 Results from Immersion Rectangle Tests

The data available from immersion rectangle tests was limited, due primarily to the relatively small specimens. Table 2 shows the skewing angles for the parent metals and the welds, using the mild steel rectangle as reference. The results indicate considerable scatter from this technique. As these readings are not compatible with the more elaborate techniques (see section 4.1), it is likely that this inherently limited approach is not reliable. For example, the copper LT specimen exhibits less skewing than the titanium rectangles. It should also be appreciated that this technique uses a point reading only, not a comprehensive scan.

4.3 Results from the Contact Rectangle Technique

Figure 8a shows a sample plot from mild steel, which shows a very uniform (gaussian) profile. Figure 8b, a similar plot from stainless steel, shows a very non-uniform plot due to the anisotropy of the material. The results can be summarized by saying that the mild steel

and titanium alloys showed fairly uniform plots, as expected, while the stainless steel, copper, Inconel and Hastelloy all showed predictably non-uniform plots. These results broadly agreed with those from the immersion cylinder tests.

4.4 Results from the Contact Cylinder Tests

Comprehensive isometric plots were made for all the materials using the contact cylinder technique. Figure 9a shows mild steel, though the profile shows considerable non-uniformity. This indicates the degree of scatter inherent in this technique, since mild steel is known to be an ultrasonically isotropic material. As further examples, Figure 9b shows the titanium grade 2 profile, and 9c the titanium grade 12 HT profile. Both show considerably greater experimental scatter than the immersion cylinder technique. The stainless steel, Inconel, Hastelloy and copper all showed essentially random beam skewing with this technique, as illustrated by the Hastelloy HT isometric in Figure 9d. This contact cylinder technique is limited by two factors: (i) problems with coupling, as discussed before, and (ii) the limited contact area available with a flat shoe on a curved surface.

5.0 DISCUSSION

5.1 Evaluation of the Techniques

The initial contract for shear wave beam skewing was to develop a technique for measuring beam skew in the candidate weld materials /22/. The criterion used was whether or not a signal could be obtained, rather than the quality of the signal. On this basis, four techniques were developed for this quantification phase /23/. Results using the four techniques were obtained in this second phase, and it is apparent that the immersion cylinder technique is the most reliable. The two contact techniques suffered from predictable shear wave coupling problems, and the contact cylinder technique was also limited in the contact area. The immersion rectangle technique produced only limited data due to the small area available. Unfortunately the immersion cylinder technique was not perfect either. Beam skewing in the vertical plane could be extensive, making data gathering and presentation a problem. The UT PATH computer program is not capable of handling three dimensional beam paths. Furthermore, each weld is inherently different from the next, though this will apply to any characterization technique. However, despite its limitations, the immersion cylinder technique appears to be the most repeatable and reliable technique for characterizing shear wave beam skewing in candidate weld materials.

5.2 Implications of the Results

The immersion cylinder shear wave results are in broad agreement with the longitudinal wave results /3/, where mild steel and titanium showed little beam skewing, though copper, stainless steel, Inconel and Hastelloy all showed potential inspection problems. For the shear wave characterization, the mild steel and titanium grade 2 showed negligible beam skewing, while the titanium grade 12 showed some distortions. The stainless, copper, Inconel and Hastelloy all showed severe beam skewing (see Figure 7 and Table 1) though the Hastelloy and copper were noticeably worse than the stainless. The shear waves in this experimental procedure were polarized in the vertical plane (SV waves), and computer modelling by Ogilvy /24/ has indicated that SV waves are more seriously skewed than longitudinal waves. SH waves (horizontally polarized shear waves) apparently are less seriously skewed, though these are extremely difficult to generate under normal conditions. Typically an EMAT device, or non-contact transducer, is used to generate such a wave, and such devices present serious inspection problems, such as very poor sensitivity.

For practical in-service inspections, including nuclear used fuel container final closure welds, beam skewing can be a major problem. The physics of beam skewing indicates that the amount of skewing will also be a function of the thickness of the component. Thus thin-walled containers made of Inconel, Hastelloy or stainless steel are likely to be a simpler inspection problem than a thick walled container made of copper, even if copper does not skew (longitudinal wave) beams as severely as, say, stainless steel. In practice, a number of ultrasonic probes have been developed commercially for inspections through cladding in nuclear stations, either stainless or Inconel. These probes typically use a twin crystal longitudinal wave, and are used for looking for underclad cracking at depths of 5-10 mm. The results from the longitudinal and shear wave characterization suggest that similar technology, tailored to the final closure weld, could probably be of use here too.

For thicker materials, there are a number of on-going projects supported by EPRI in the U.S. to improve the inspectability of centrifugally-cast stainless steel. These techniques include extensive signal averaging to differentiate grain "noise" from defects, adaptive learning (or artificial intelligence), and other differentiation techniques/25/. While these techniques are primarily aimed at detecting and measuring intergranular stress corrosion cracking, they should be of considerable use to the problem of inspecting final closure welds made from ultrasonically anisotropic materials. There are a number of other possible improvements, for example the influence of test frequency could be investigated, and the effect of attempting to decrease grain growth by, say, doping. As with the longitudinal wave results, there was no significant trend with weld interpass temperature with the shear waves.

The results can be summarized by saying that, from a Remote Inspection viewpoint, the most desirable material for a used fuel container would be titanium, preferrably grade 2 titanium. Copper would likely present considerable problems, due to its beam skewing and to the thickness of material required. Stainless, Inconel or Hastelloy would also present problems due to beam skewing, though the thin material would be an improvement. It should be mentioned that for a titanium fusion weld, there is no method of quantifying the oxygen pick-up at the moment, except by looking at the colour of the weld. This particular problem would be solved by using diffusion bonds, which are readily inspectable /26/.

6.0 CONCLUSIONS

1. Of the four shear wave characterization techniques developed (immersion cylinder, immersion rectangle, contact rectangle and contact cylinder), the immersion cylinder technique generated the most repeatable results.

2. The immersion cylinder technique showed that:

   (i) titanium grade 2 was highly isotropic;

   (ii) titanium grade 12 was fairly isotropic, but showed some amplitude trends;

   (iii) the copper welds and one of the Hastelloy welds showed almost random beam skewing; and

   (iv) the stainless, Inconel and the other Hastelloy weld showed severe beam skewing.

3. From a Remote Inspection viewpoint, copper, Inconel and Hastelloy will present major inspection problems, while titanium should present less beam skewing problems.

7.0 RECOMMENDATIONS

1. Further work should be performed on evaluating these welds eg by looking at frequency effects.

2. Programs like the EPRI contracts on inspection of centrifugally cast stainless steel, should be monitored for future developments.

Recommended:

J.A. Baron
Supervising Engineer
Nondestructive & Fracture
Evaluation Section

Approved:

J. Brown
Manager
Metallurgical Research Dept

Prepared:

M.D.C. Moles
Engineer-NDE
Nondestructive & Fracture
Evaluation Section

E.A. Ginzel
Ginzel Brothers & Associates

R.K. Ginzel
Ginzel Brothers & Associates

Reviewed:

J.A. Chadha
Area Co-Ordinator
AECL Technical Assistance
Program

REFERENCES

1. K. Nuttall, J.L. Crosthwaite, P.J. McKay, P.M. Mathew, B. Teper, P.Y.Y. Maak and M.D.C. Moles, Materials Research Society 6th International Symposium on the Scientific Basis for Nuclear Waste Management, Boston, MA. November 1-4, 1982.

2. K. Nuttall, Proceedings of the Fourteenth Information Meeting of the Nuclear Fuel Waste Mangement Program (1982 General Meeting), Winnipeg, Manitoba, September 15-16, 1982. (Also AECL Technical Record TR-207, December 1982).

3. M.D.C. Moles and J. Imada, OHRD Report No 84-227-K, August 22, 1984.

4. G.J. Dau, I. Mech. E. Conference Paper C212/76, 1976.

5. B.R. Dewey, L. Adler, R.T. King and K.V. Cook, Experimental Mechanics, November 1977, p. 420.

6. S.J. Mech, J.S. Emmons, and T.E. Michaels, Proceedings of the First International Symposium on Ultrasonic Materials Characterization, Gaithersburg, Maryland, June 7-9, 1978. Issued as NBS Special Publication 596, September 1980, p. 561.

7. L. Adler, K.V. Cook and D.W. Fitting, idem, p. 533.

8. M.G. Silk, Materials Evaluation, vol 39, April 1981, p. 462.

9. D.S. Kupperman, K.J. Reimann and N.F. Fiore, Materials Evaluation, April 1978, p. 70.

10. D.S. Kupperman and K.J. Reimann, IEEE Transactions on Sonics and Ultrasonics, vol SU-27, No. 1, January 1980, p. 7.

11. D.S. Kupperman, K.J. Reimann and D.I. Kim, Proceedings of Symposium on "Nondestructive Evaluation: Microstructural Characterization and Reliability Strategies", sponsored by TMS-AIME and ASM, Pittsburgh, PENN, October 5-9, 1980, Ed. by O. Buck and S.M. Wolf, p. 199.

12. D.S. Kupperman, K.J. Reimann and A. Winiecki, Materials Evaluation, Vol 39, May 1981, p. 527.

13. P. Caussin, J. Cermak and D. Verspeelt, 4th International Conference on Nondestructive Evaluation in the Nuclear Industry, Lindau, West Germany, May 25-27, 1981.

14. X. Edelmann, NDT International, June 1981, p. 1.

15. M.G. Silk, Ultrasonics, September 1981, p. 208.

16. M.K. Murali and K. Neelakantan, NDT International, December 1981, p. 321.

17. D. Heinrich, G. Muller nd M. Weiss, NDT International, August 1982, p. 179.

18. D.S. Kupperman, K.J. Reimann and D. Yuhas, Proceedings of Conf. on "Quantitative NDE in the Nuclear Industry", Publ. by American Society for Metals, Metals Park, OH (1983), San Diego, Calif, May 1982, p. 172.

19. L.A. Lott and R.K. Malik, Materials Evaluation, vol 41, May 1983, p. 738.

20. J. Tomlinson, A. Wagg and M. Whittle, Proceedings of International Conference on "Nondestructive Evaluation in the Nuclear Industry, Salt Lake City, Utah, February 13-15, 1978, p. 64.

21. A. Singh, Ultrasonics, November 1983, p. 270.

22. Ginzel Brothers, "Skewing of Shear Waves in Candidate Materials for Nuclear Waste Fuel Containers, Part I: Techniques", June 1985.

23. Idem, "Part II: Results", December 1985.

24. J.A. Ogilvy, NDT International, April 1985, p. 67.

25. M. Behravesh, 7th Int Conf on NDE in the Nuclear Industry, Grenoble, France, Jan 28 - Feb 1, 1985.

26. M.D.C. Moles and A.L. Allen, 11th World Conference on Nondestructive Testing, Las Vegas, Nevada, Nov 2-8, 1985.

TABLE 1

SAMPLE BEAM SKEWING RESULTS FROM IMMERSION CYLINDER TESTS

CYLINDER	PLOTWIDTH AVERAGE	ST. DEV.	SKEWANGLE AVERAGE	STD. DEV+	POSITION (SEE TEXT)
MILD STEEL ROD	59.21	8.81	-1.27	2.28	C
STAINLESS STEEL WELD	87.24	37.91	-2.94	12.44	A
	87.87	38.84	-4.65	20.35	B
	80.32	35.83	-2.63	12.12	C
Ti GRADE 2	55.05	4.91	-1.77	3.12	C
INCONEL 625 LT* WELD	130.36	38.69	14.64	32.83	A
	118.14	33.88	15.38	25.73	B
	79.96	25.54	8.08	21.03	C
	89.89	29.00	15.50	24.71	D
	78.87	23.58	10.63	21.29	E
INCONEL 625 HT* WELD	105.11	29.24	4.73	18.52	A
	103.92	31.37	10.34	16.31	B
	89.34	33.69	16.59	20.12	C
	71.47	29.59	13.55	13.34	D
	73.78	29.97	3.24	15.16	E
Ti GRADE 12 LT	63.54	18.85	0.31	11.44	A
	63.57	19.61	-1.58	10.74	C
	97.03	38.81	14.82	20.74	E
Ti GRADE 12 HT	60.01	19.32	2.99	11.79	A
	56.67	14.23	1.31	8.58	C
	91.24	39.48	7.4	18.59	E
HASTELLOY C-276 LT	122.08	28.82	-6.59	31.08	C
	146.07	43.28	-13.12	49.65	E
	99.33	48.76	-29.25	39.34	F
	97.85	48.31	37.69	32.58	G
HASTELLOY C-276 HT	124.78	31.99	-3.22	22.28	A
	115.86	33.67	-30.13	30.43	C
	123.28	43.58	-32.79	47.52	E
COPPER HT	158.42	17.87	6.20	58.89	C
COPPER LT	170.69	11.60	6.33	61.87	C
PYREX	50.65	3.23	-1.36	2.91	C

+ The standard deviation of the beam skew is considered the most important parameter.

* LT = low interpass temperature
HT = high interpass temperature

TABLE 2

BEAM SKEWING FROM IMMERSION TEST ON RECTANGLES

Sample	* Average Centre of Four Scans (mm)	Offset From Mild Steel (mm)	Rank
Mild Steel (Ref) RM200	62.5	0	NA+
Inconel (Parent Metal) PI	65.3	+2.8	NR+
Titanium (Parent Metal) PT	67.5	+5.0	NR+
Stainless (Parent Metal) PS	69.5	+7.0	NR+
Copper (Parent Metal) PC	49.5	-13.0	NR+
Copper (Low Temp) WC208	64.5	+2.0	1
Copper (High Temp) WC207	46.3	-16.2	9
Hastelloy (Low Temp) WH211	50.0	-12.5	5
Hastelloy (High Temp) WH212	59.8	-2.7	2
Stainless WS201	42.8	-19.7	10
Inconel (High Temp) WI202	54.8	-7.7	3
Inconel (Low Temp) WI203	49.8	-12.7	6
Titanium G2 WT204	75.3	+12.8	7
Titanium G12 (High Temp) WT210	75.8	+13.3	8
Titanium G12 (Low Temp) WT209	72.0	+9.5	4

* Distance measured from start of scan to highest peak. Measured in mm.

\+ Since this project was to rank weld metal the parent metals were not ranked (NR).

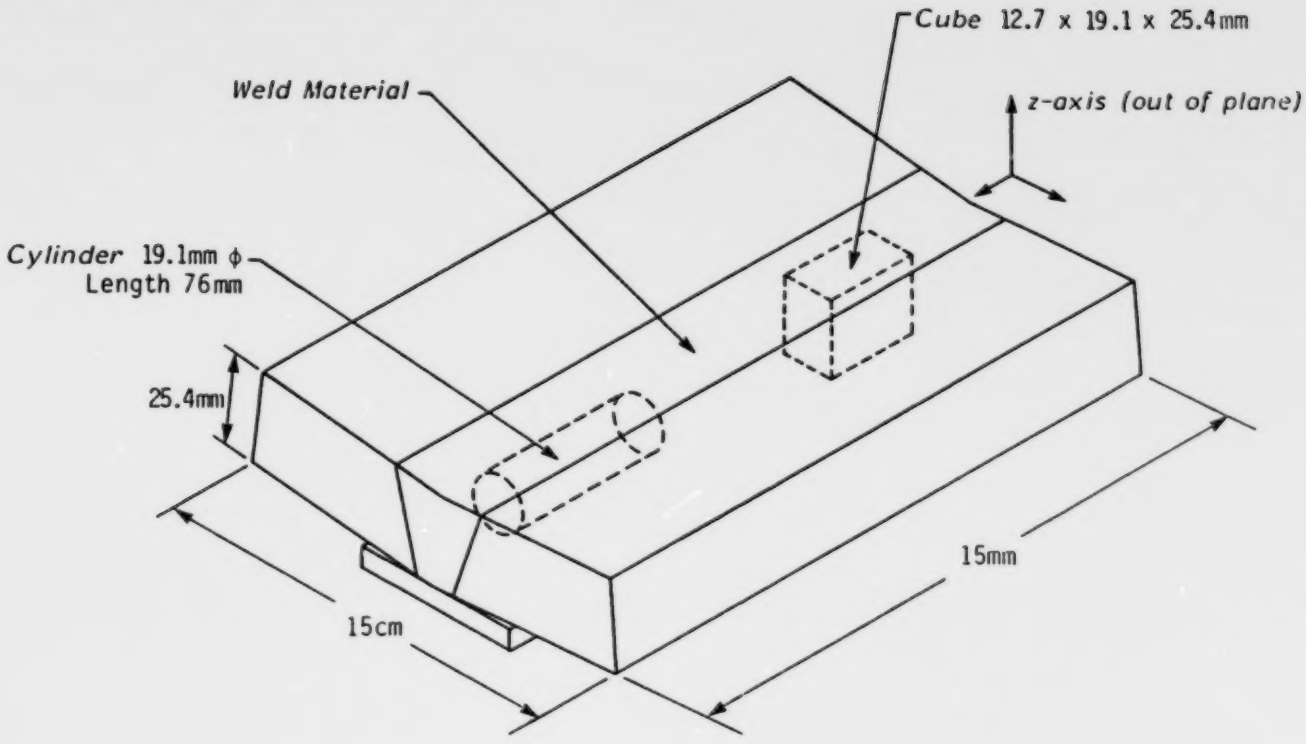


FIGURE 1
WELD LAYOUT AND SPECIMEN PREPARATION

170623 RD

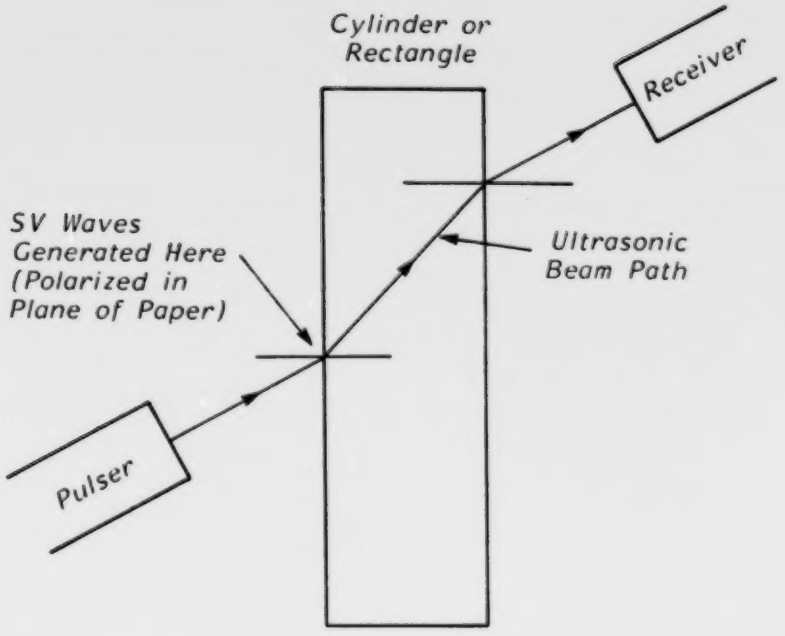


FIGURE 2
GENERATION OF SHEAR WAVES IN SPECIMENS

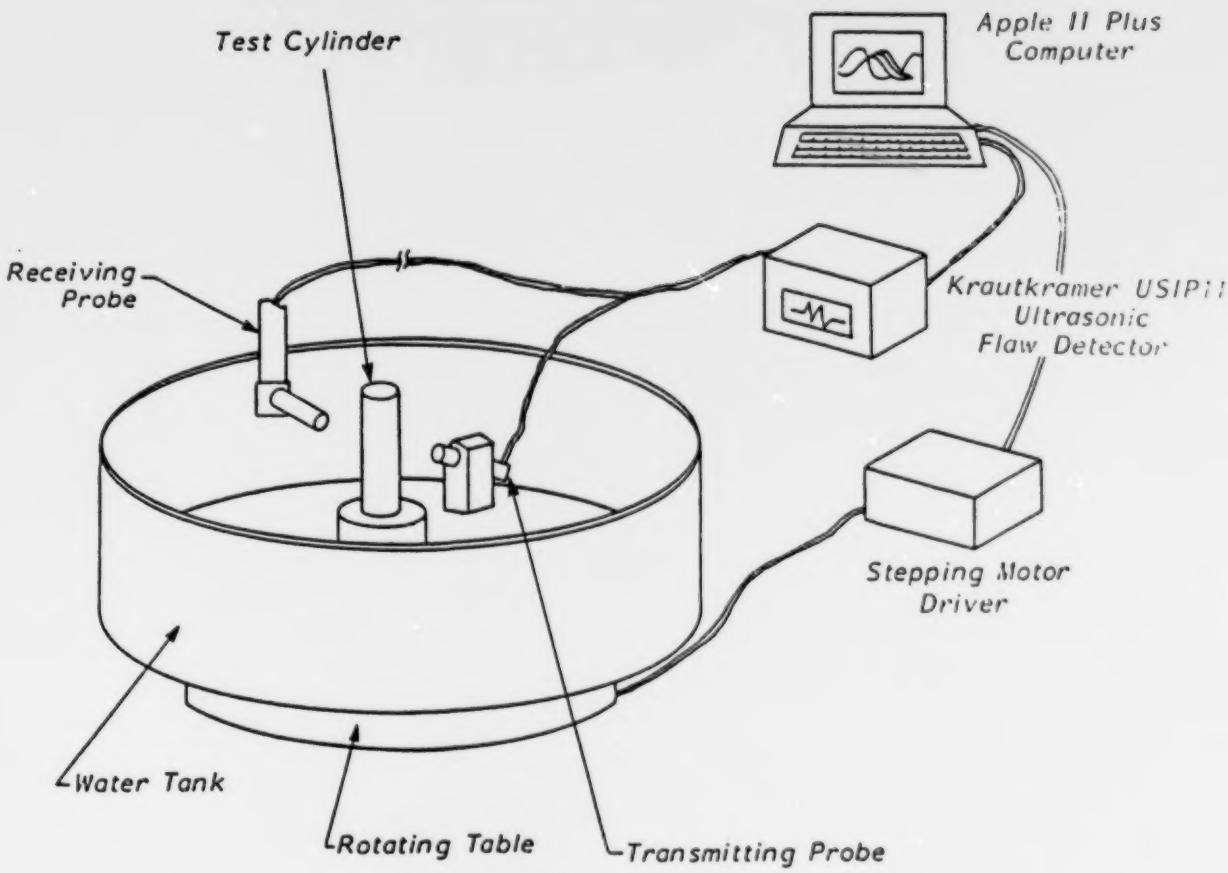


FIGURE 3

EQUIPMENT SETUP FOR GENERATING SV WAVES
USING IMMERSION CYLINDER TECHNIQUE

170625 RD

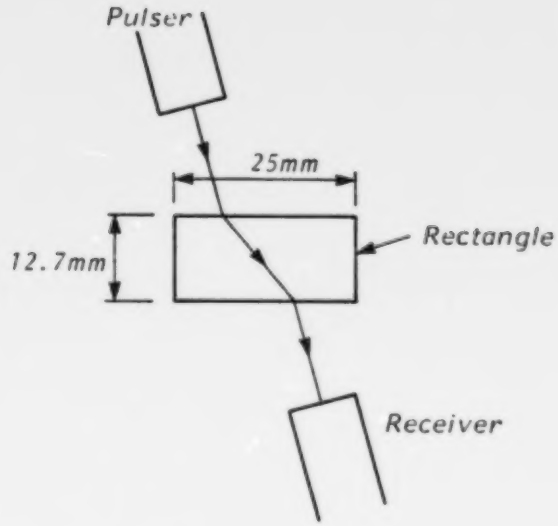


FIGURE 4

SCHEMATIC OF IMMERSION RECTANGLE
TECHNIQUE SET-UP

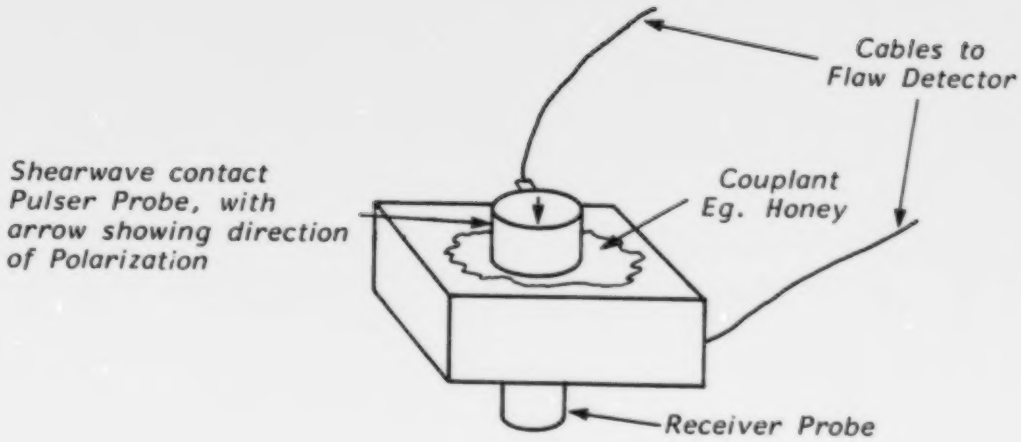


FIGURE 5

SCHEMATIC SHOWING CONTACT RECTANGLE TECHNIQUE
USING TWO POLARIZED, SHEAR WAVE PROBES

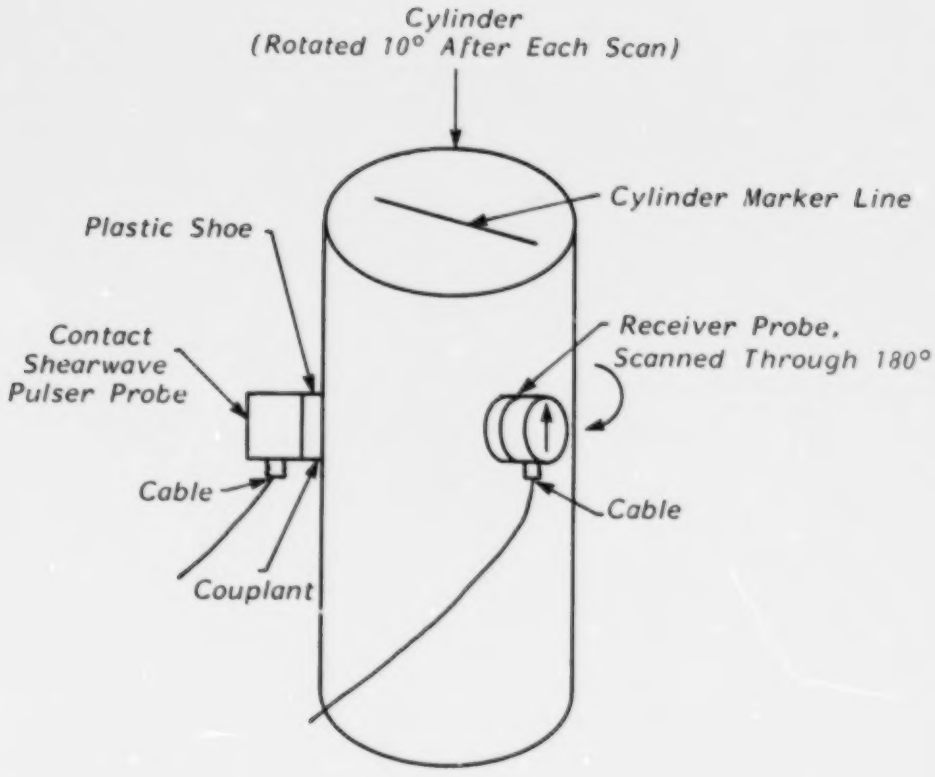


FIGURE 6
SCHEMATIC ILLUSTRATING CONTACT CYLINDER TECHNIQUE

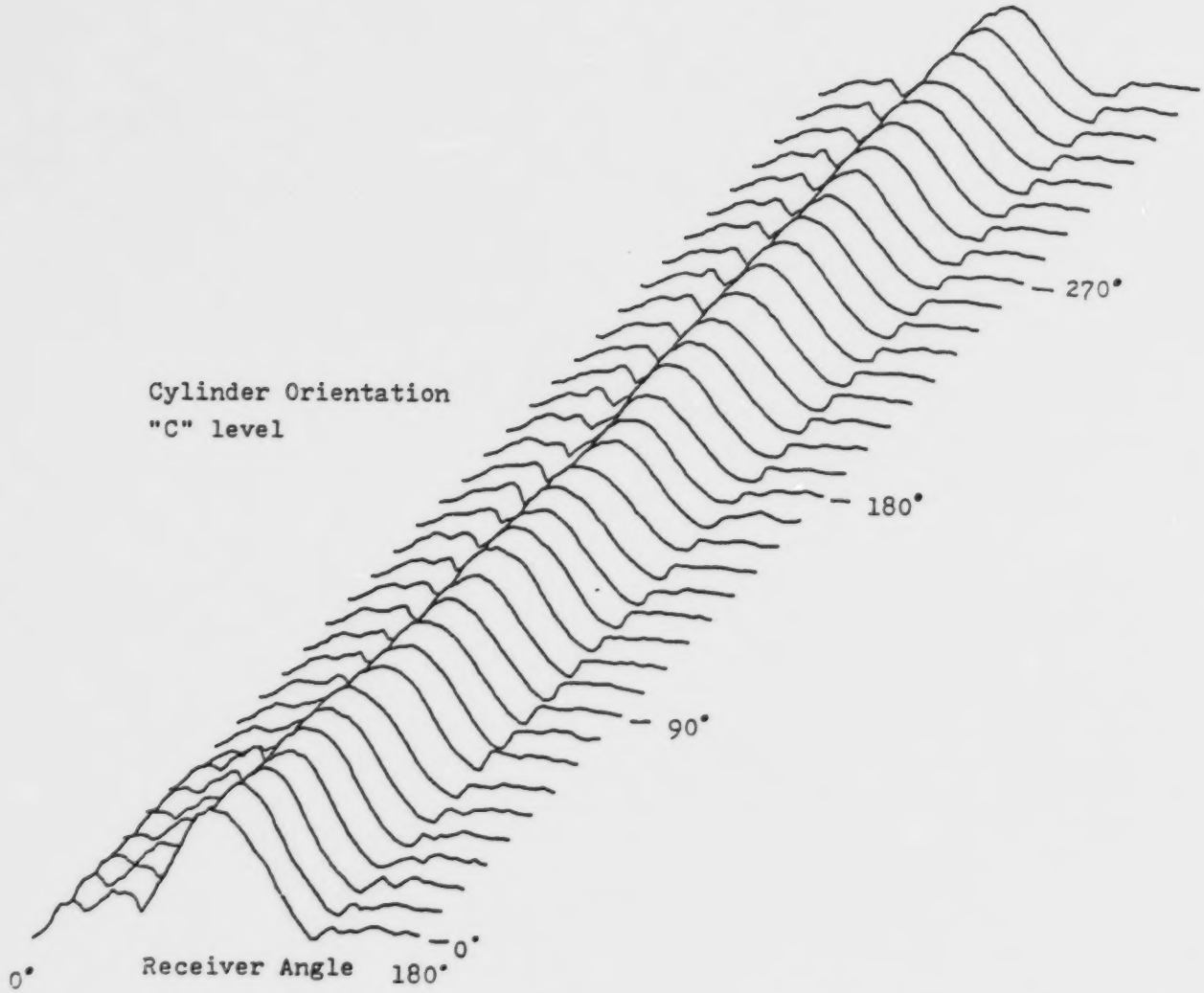


FIGURE 7
IMMERSION CYLINDER ISOMETRICS
7a - MILD STEEL

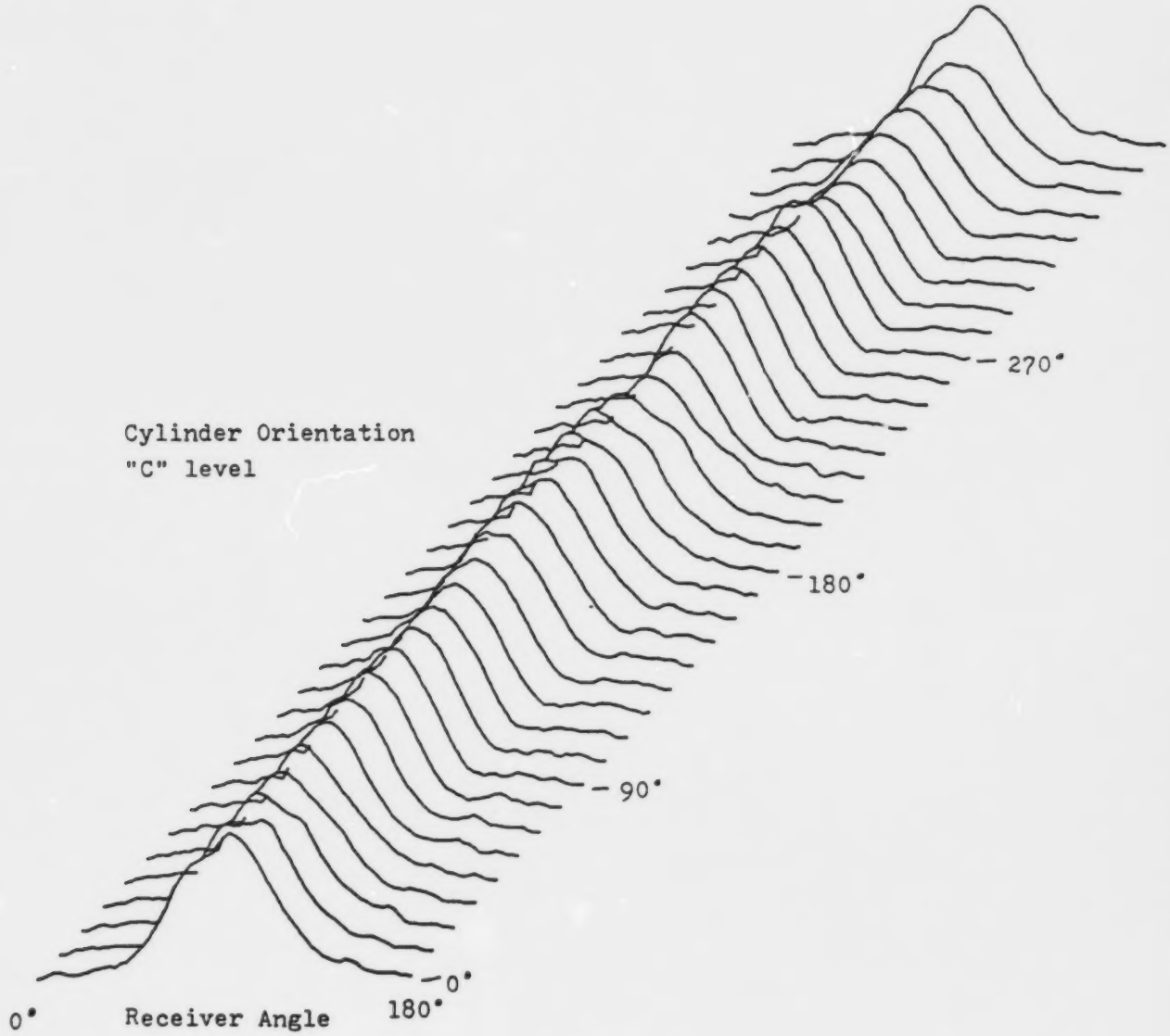


FIGURE 7b
TITANIUM GRADE 2

170630 RD

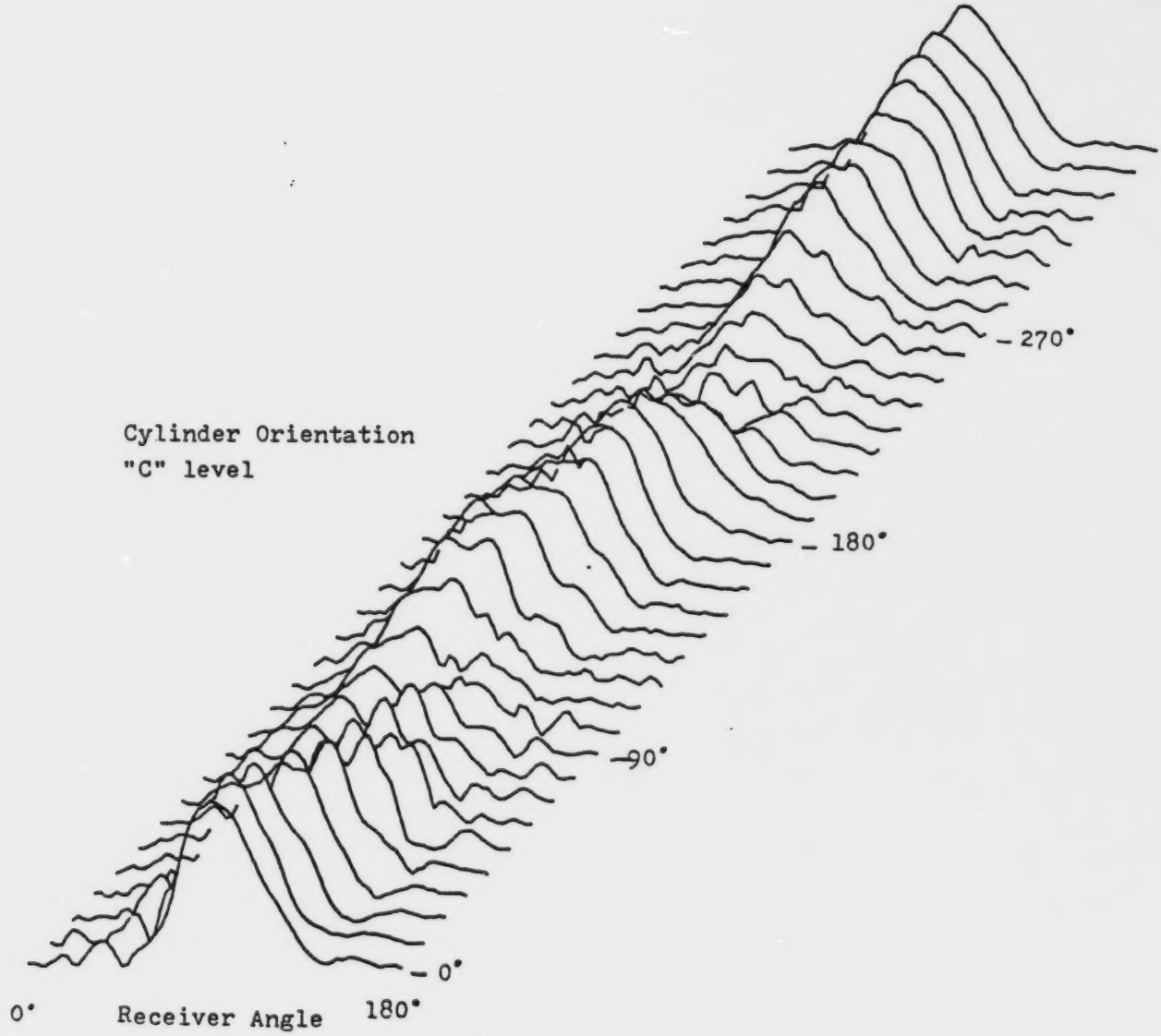


FIGURE 7c
TITANIUM GRADE 12 LT

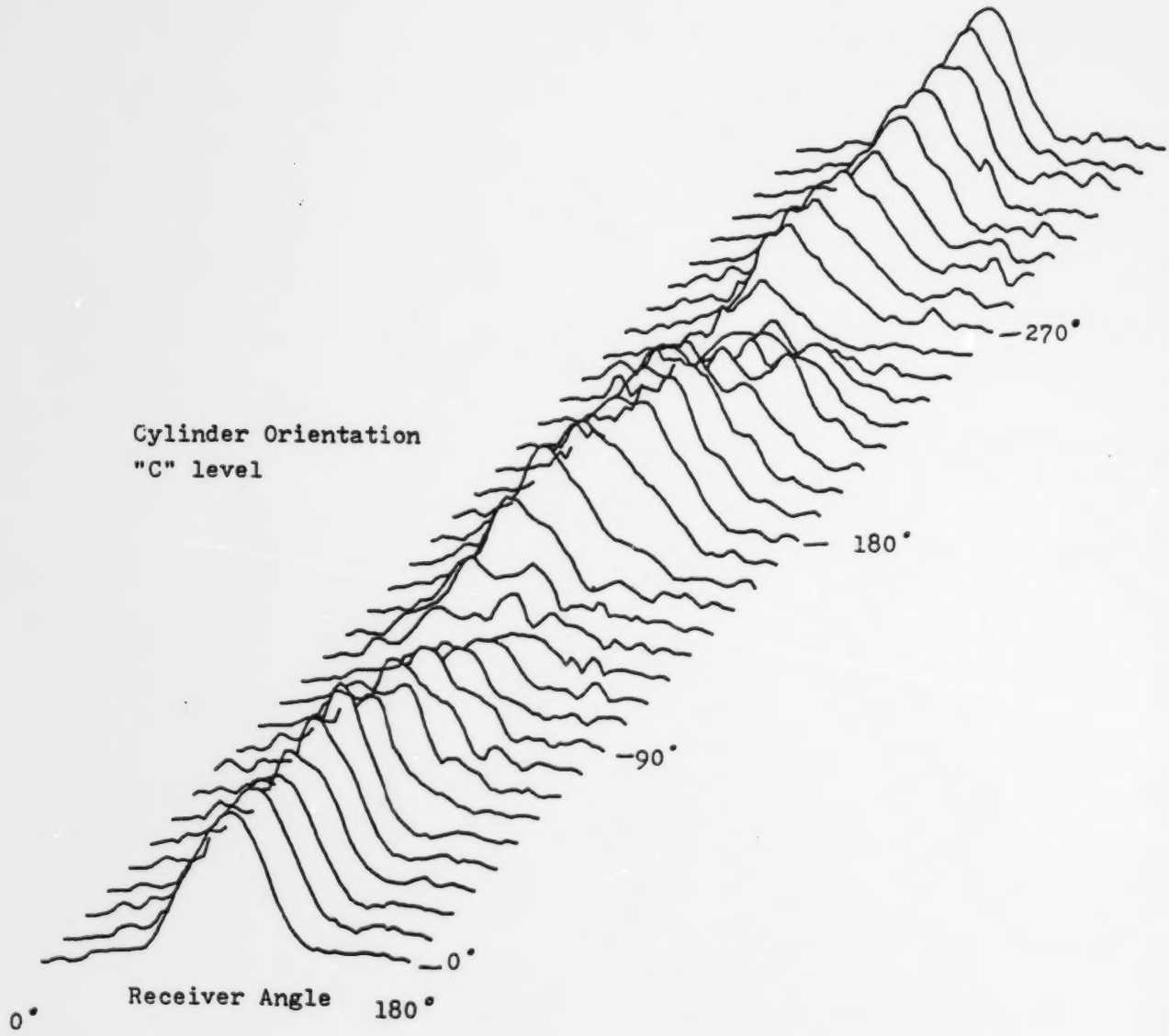


FIGURE 7d
TITANIUM GRADE 12 HT

170632 RD

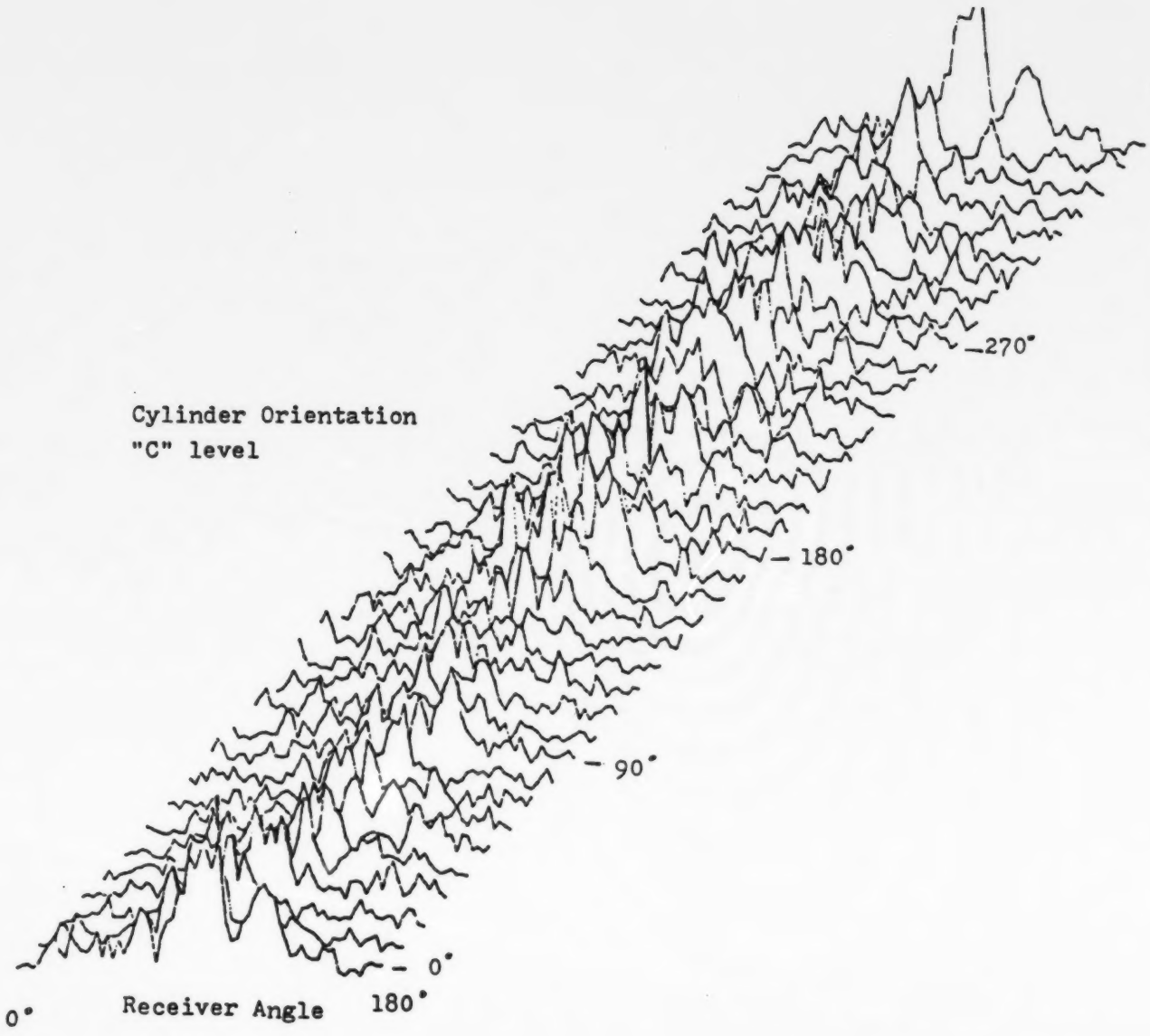


FIGURE 7e
STAINLESS STEEL

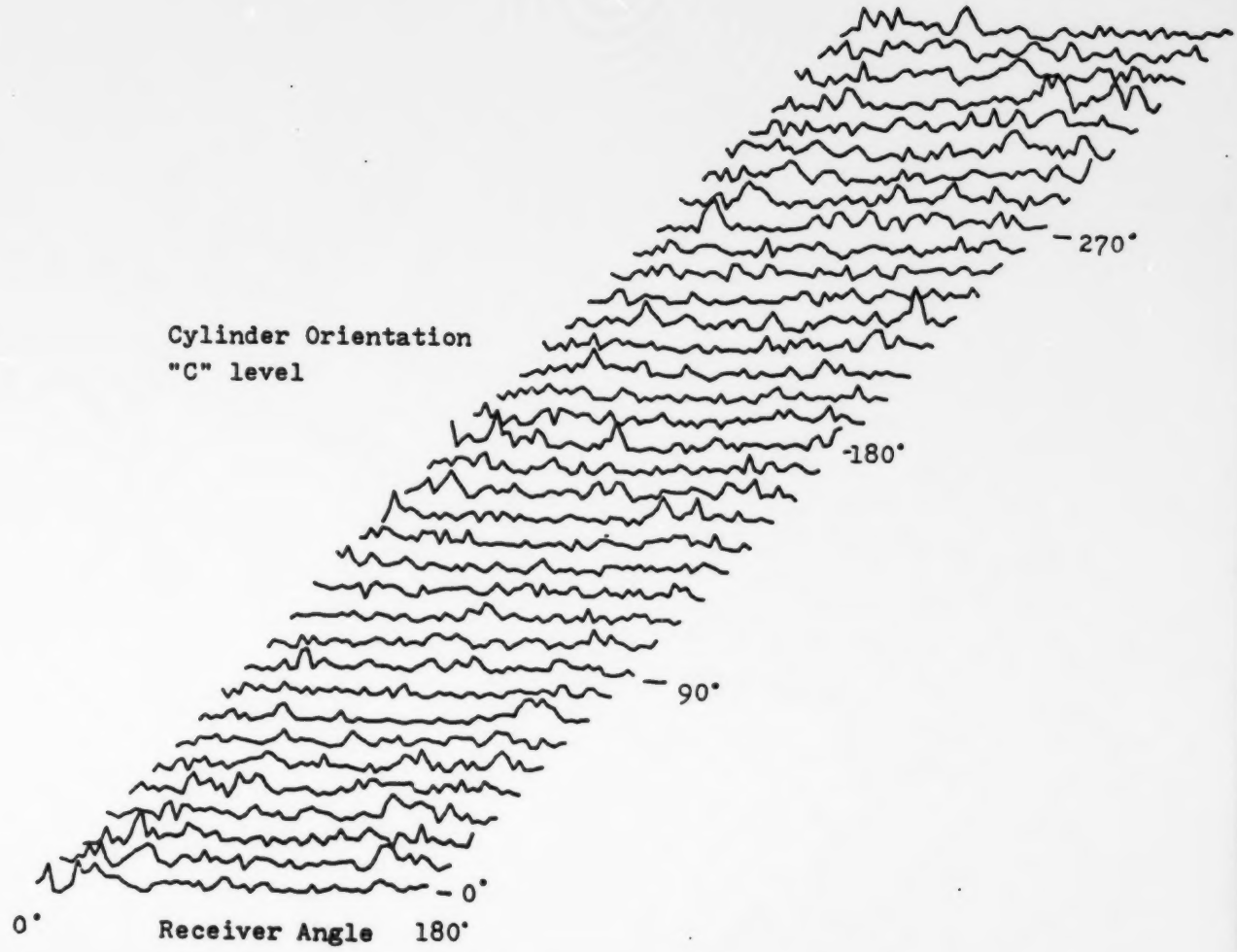


FIGURE 7f
COPPER LT

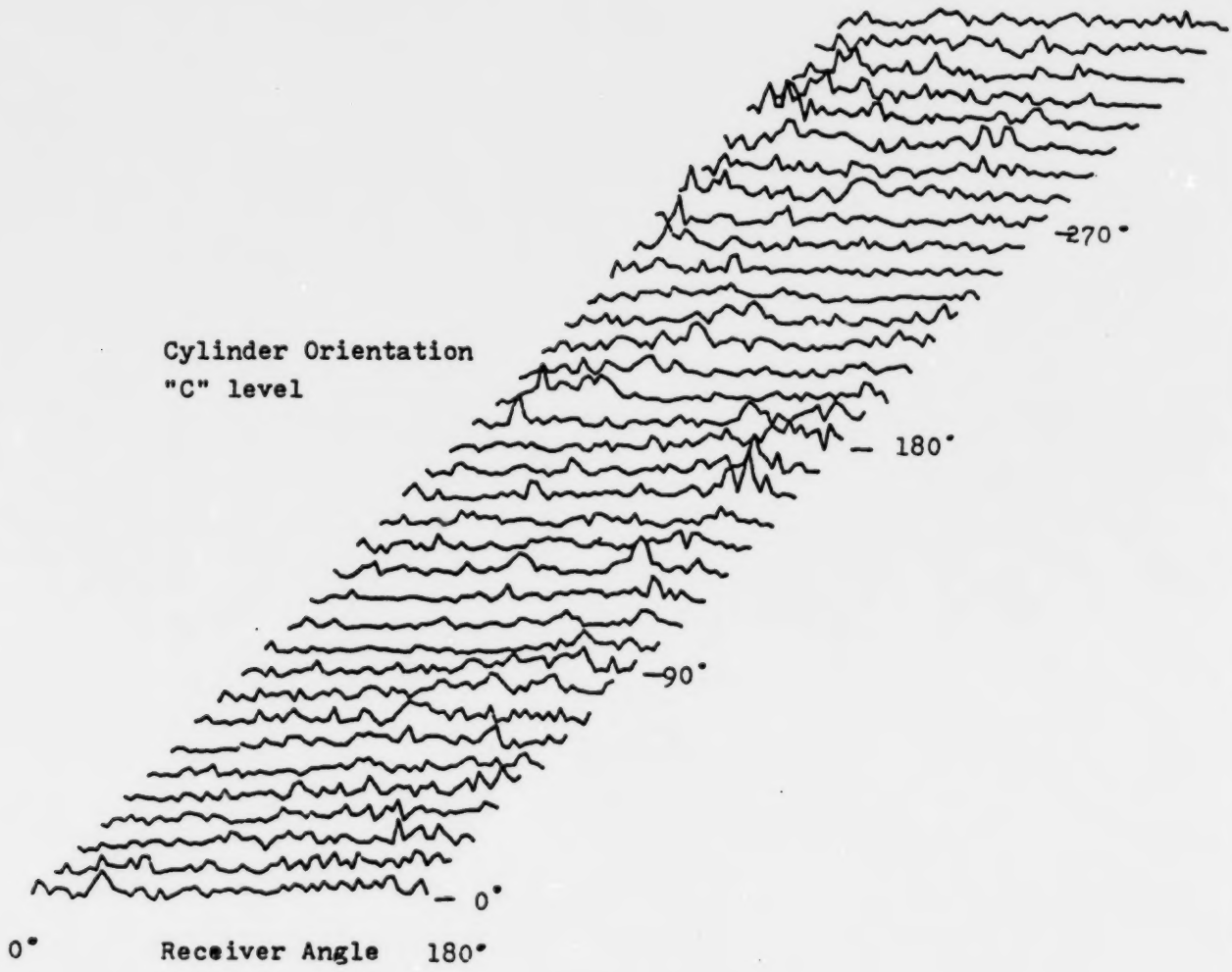


FIGURE 7g
COPPER HT

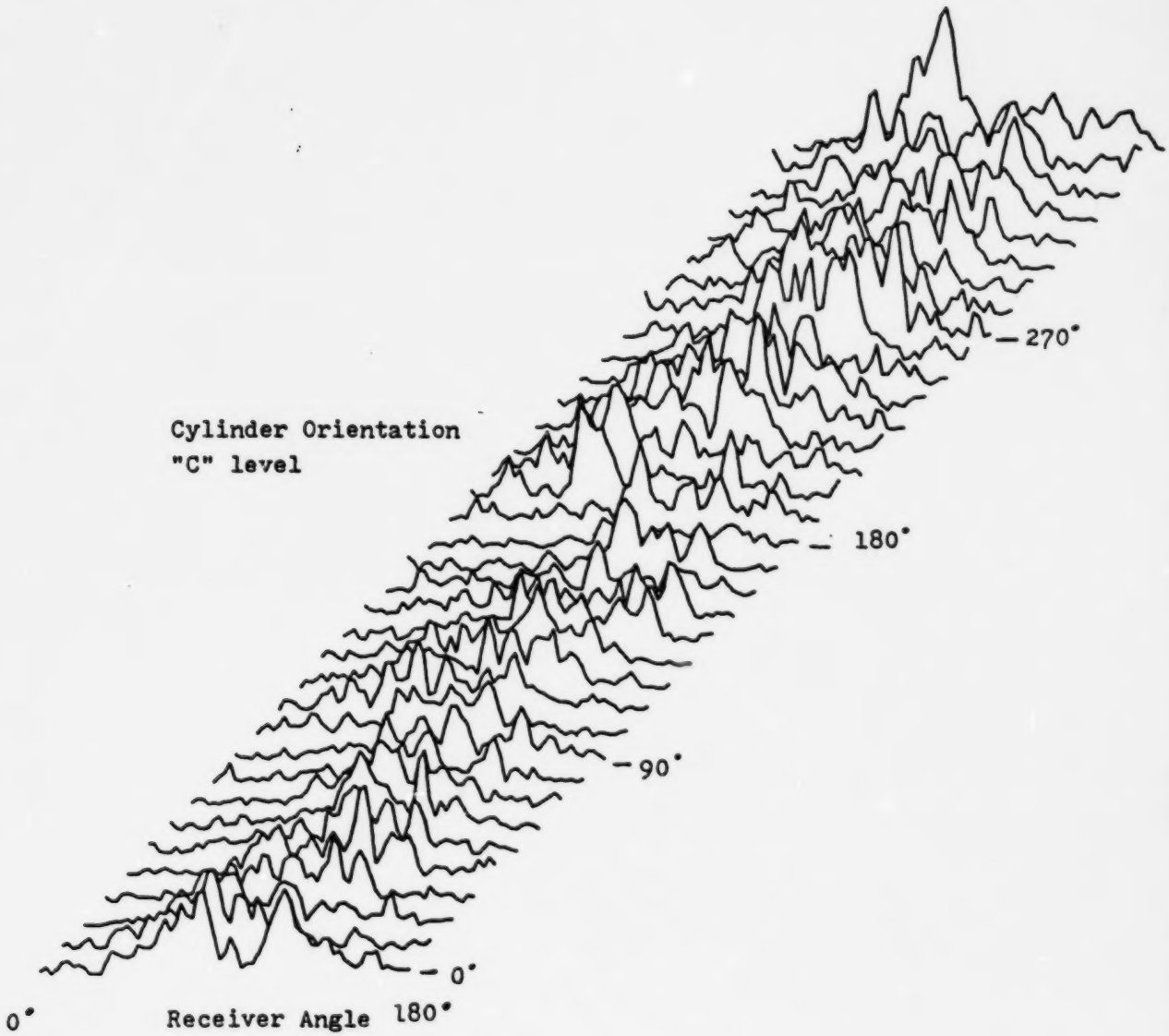


FIGURE 7h
INCONEL LT

170636 RD

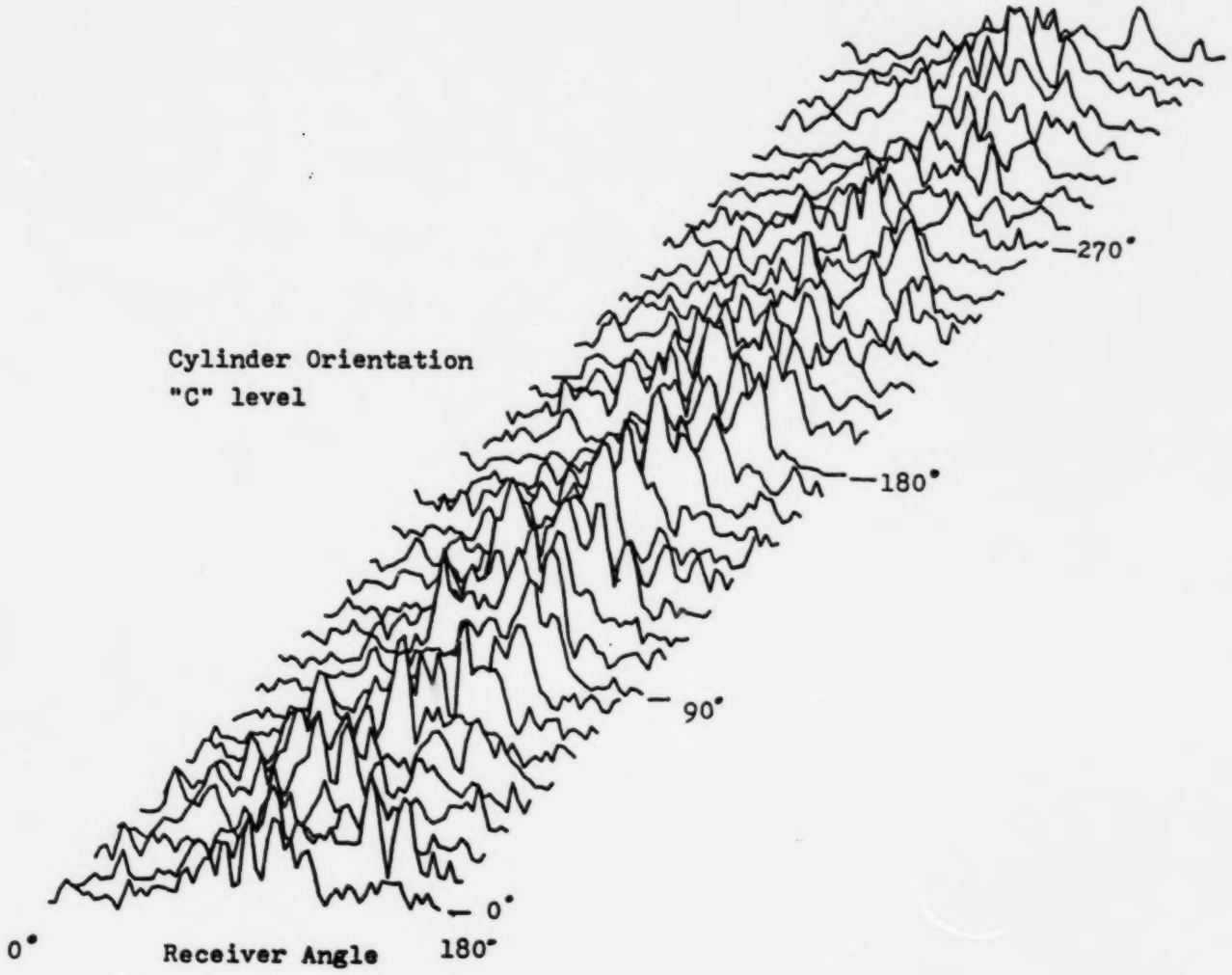


FIGURE 7i
INCONEL HT

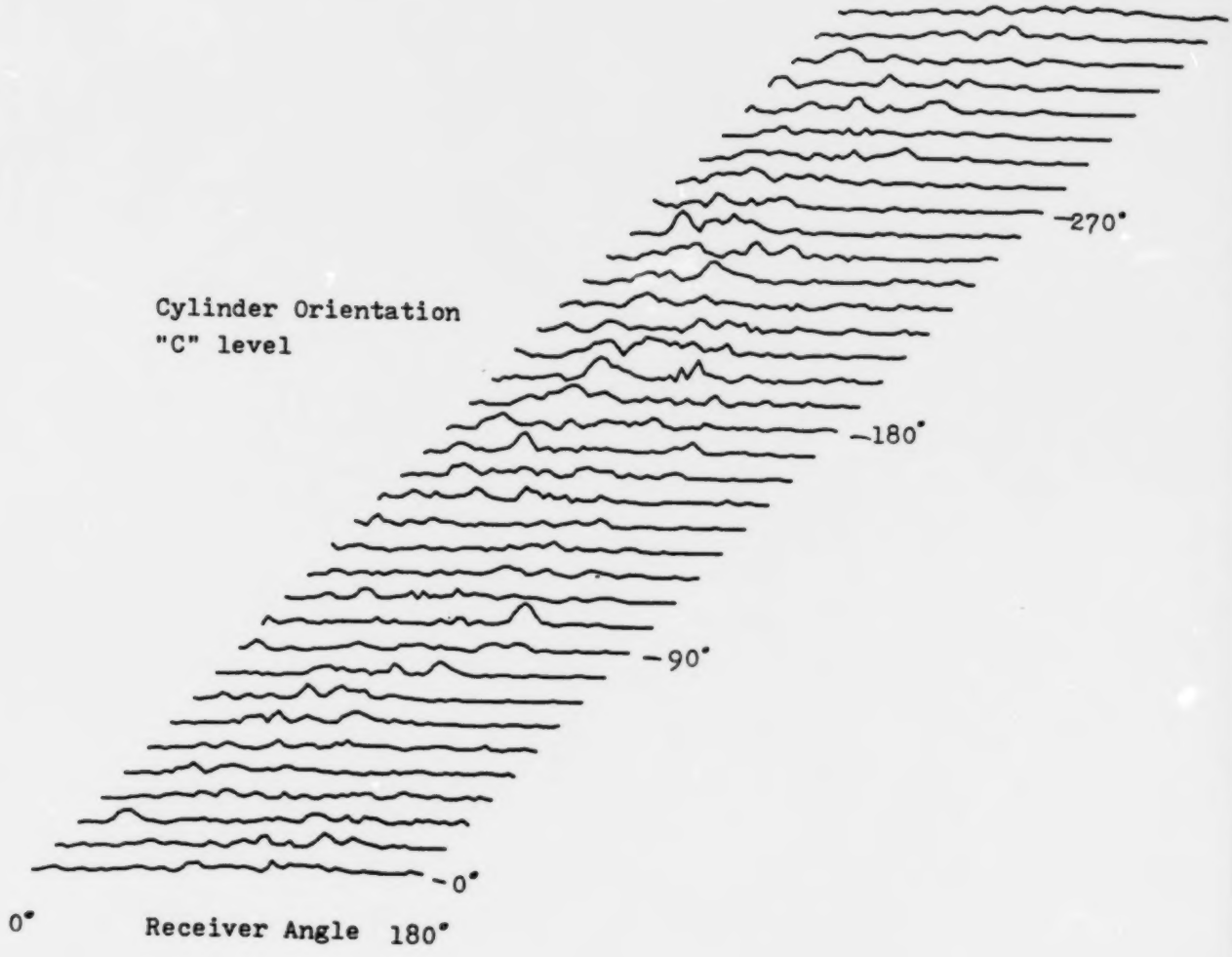


FIGURE 7j
HASTELLOY HT

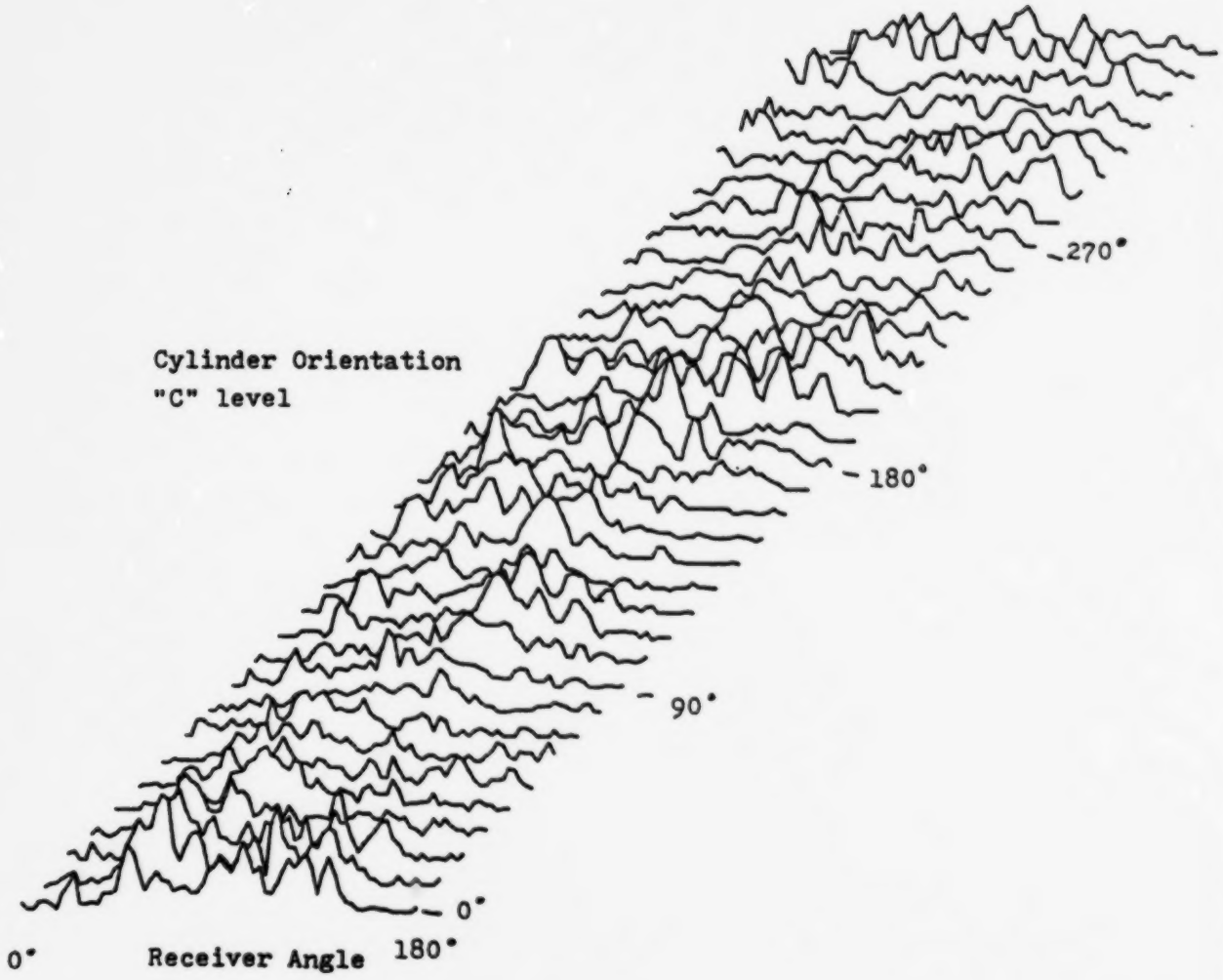


FIGURE 7k
HASTELLOY LT

170640 RD

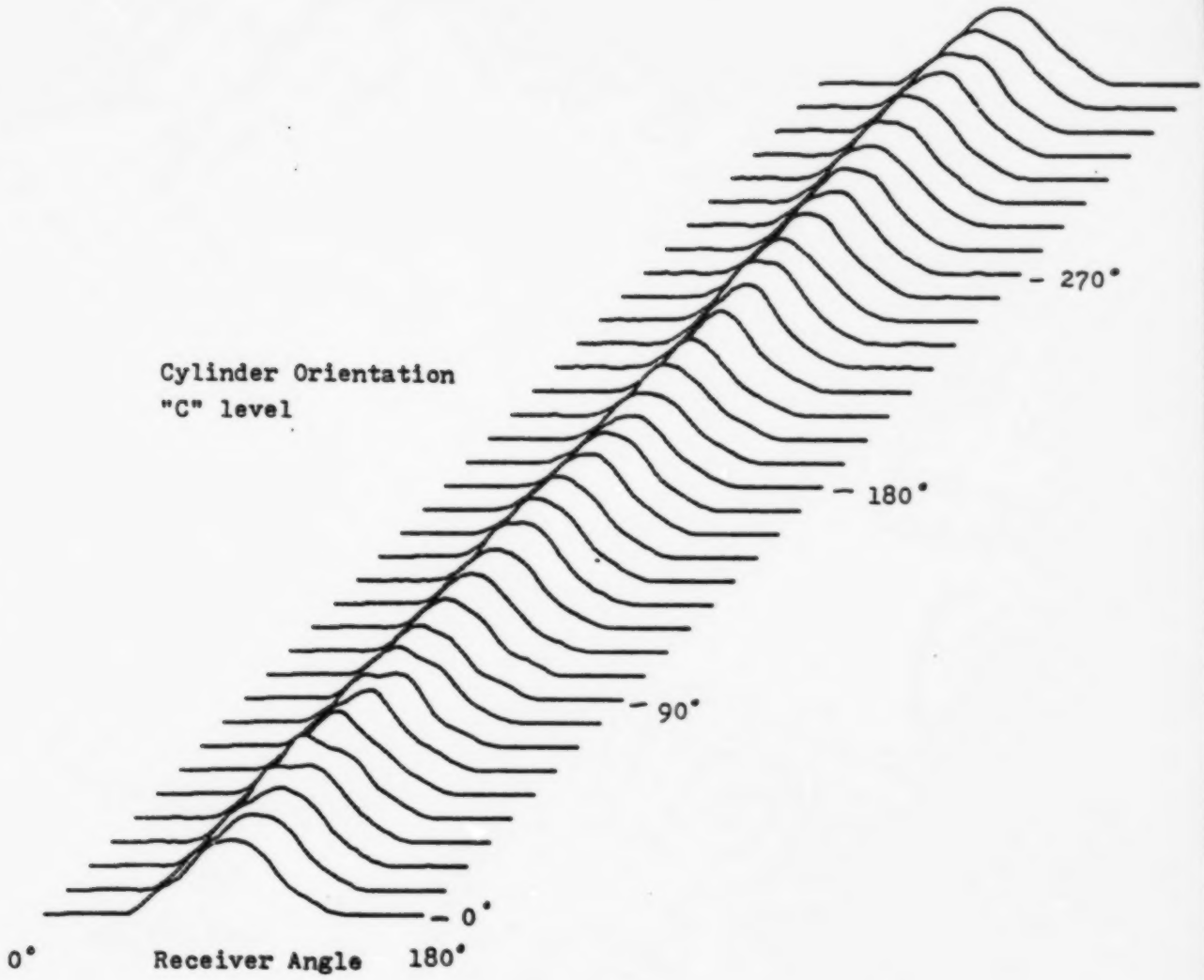


FIGURE 71
PYREX

170638 RD

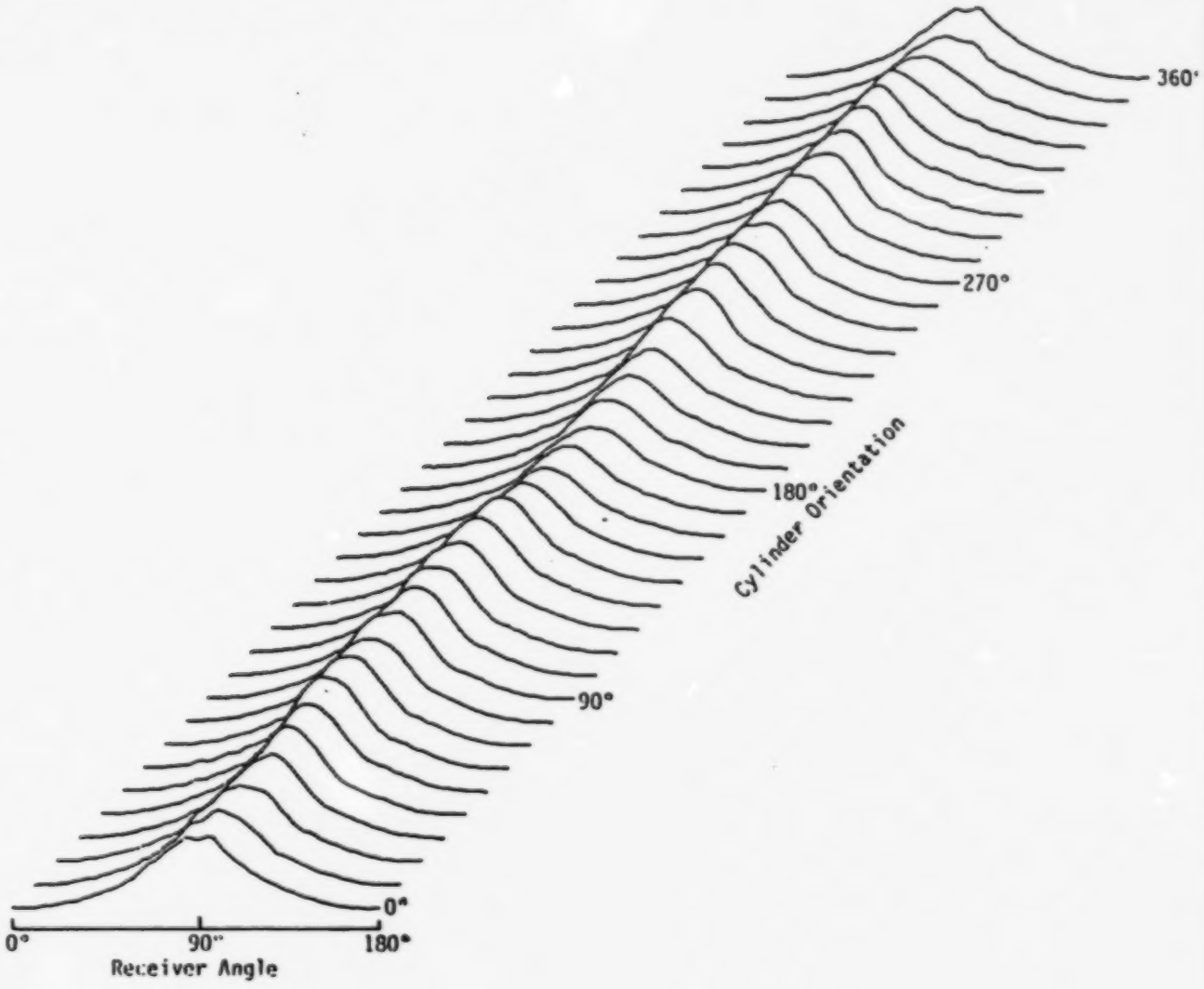


FIGURE 7m

MILD STEEL WELD - LONGITUDINAL WAVE

170641 RD

Vertical Displacement at the Same

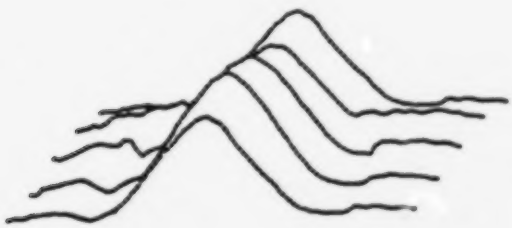
Cylinder Orientation

Mild Steel - 0°

Pyrex - 0°

Mild Steel - 90°

Mild Steel - 180°

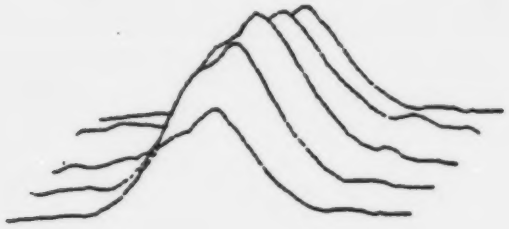


Mild Steel - 270°

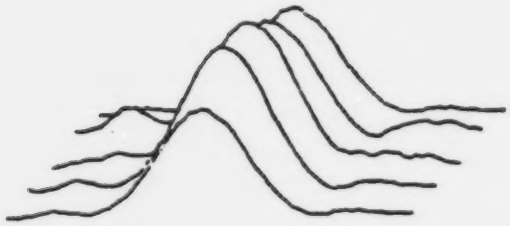
FIGURE 7n

VERTICAL DISPLACEMENT PROFILES FOR MILD STEEL

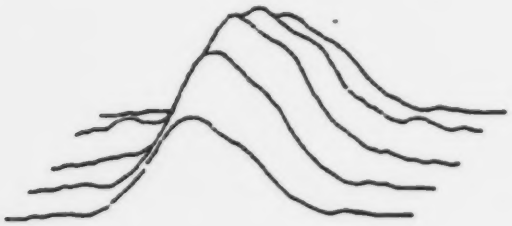
Vertical Displacement at the Same Cylinder Orientation



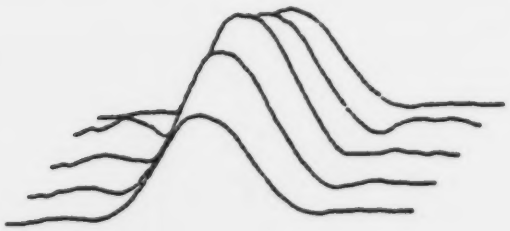
Titanium G2 - 0°



Titanium G2 - 90°



Titanium G2 - 180°



Titanium G2 - 270°

FIGURE 7o

VERTICAL DISPLACEMENT PROFILES FOR TITANIUM GRADE 2

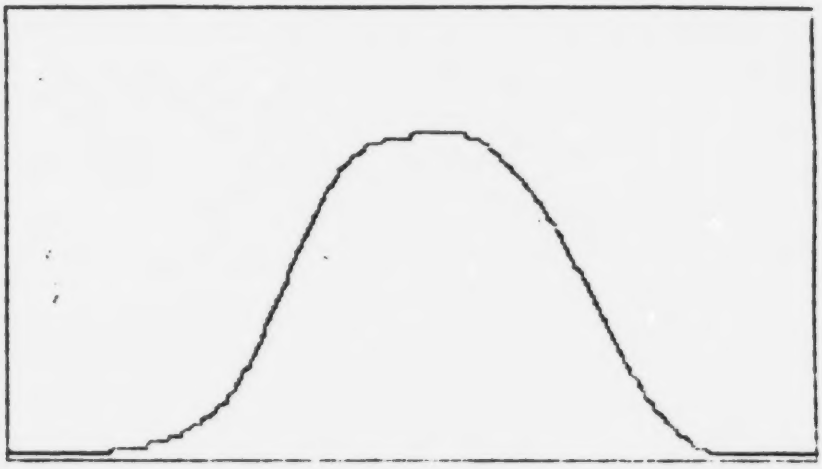


FIGURE 8a
MILD STEEL

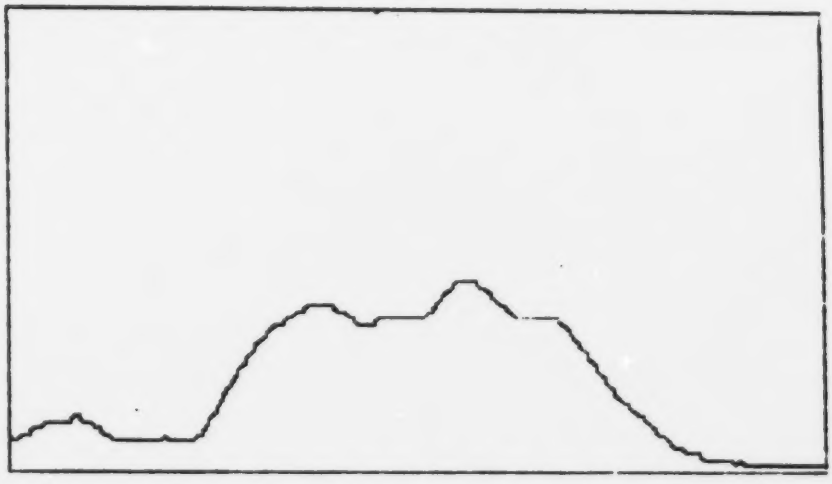


FIGURE 8b
COPPER LT
IMMERSION RECTANGLE SCANS

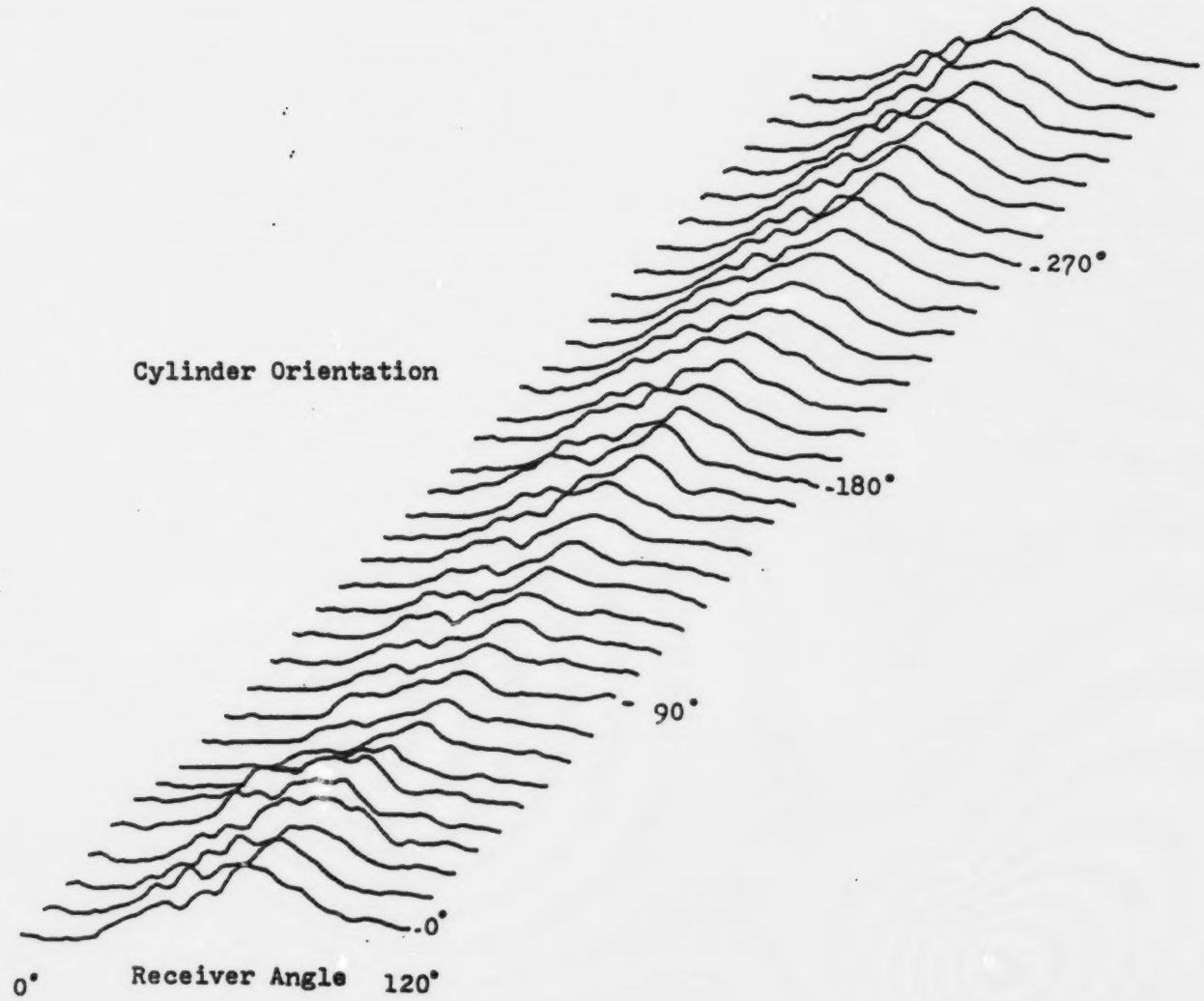


FIGURE 9
CONTACT CYLINDER ISOMETRICS
9a - MILD STEEL

170645 RD

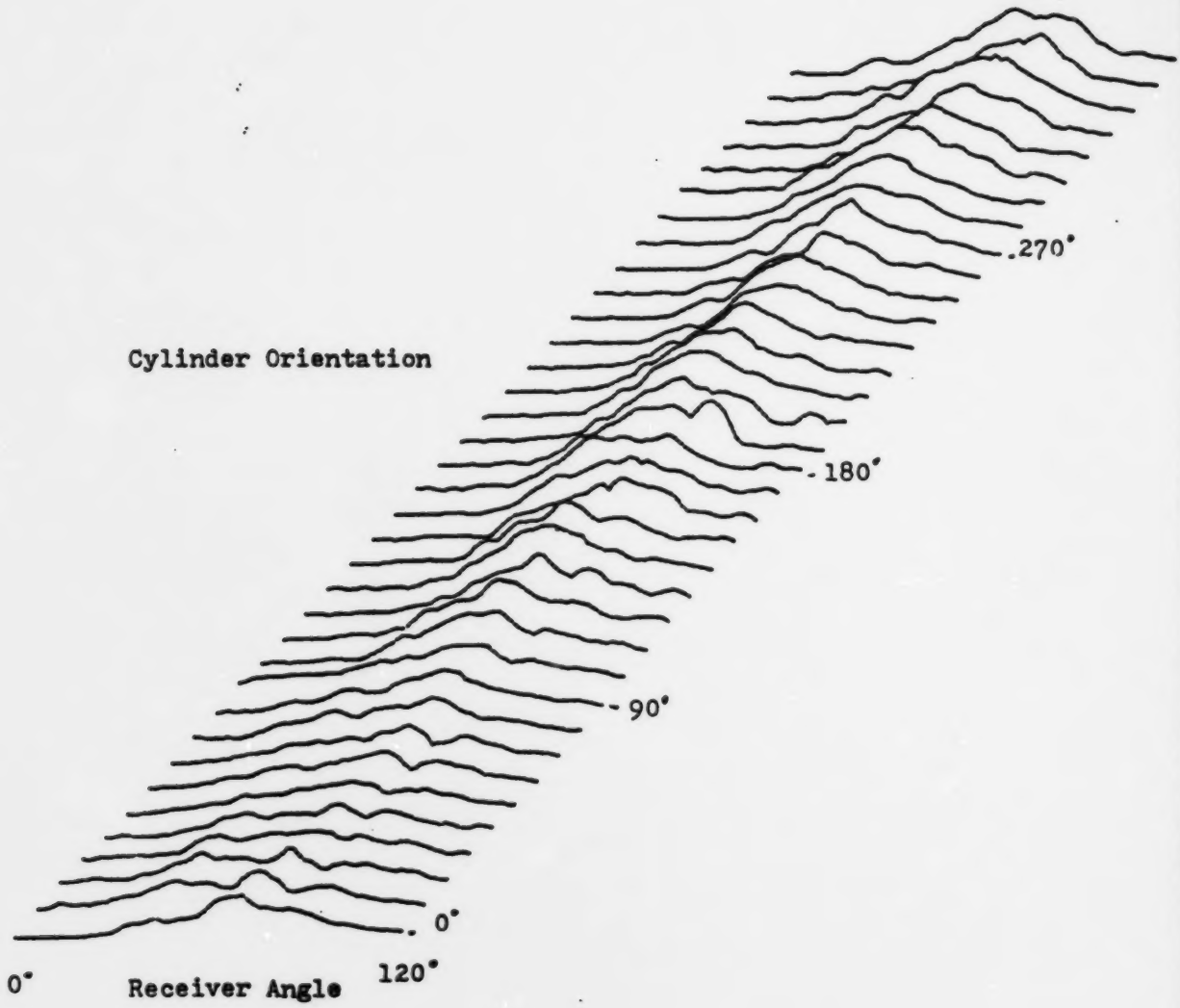


FIGURE 9b
TITANIUM GRADE 2

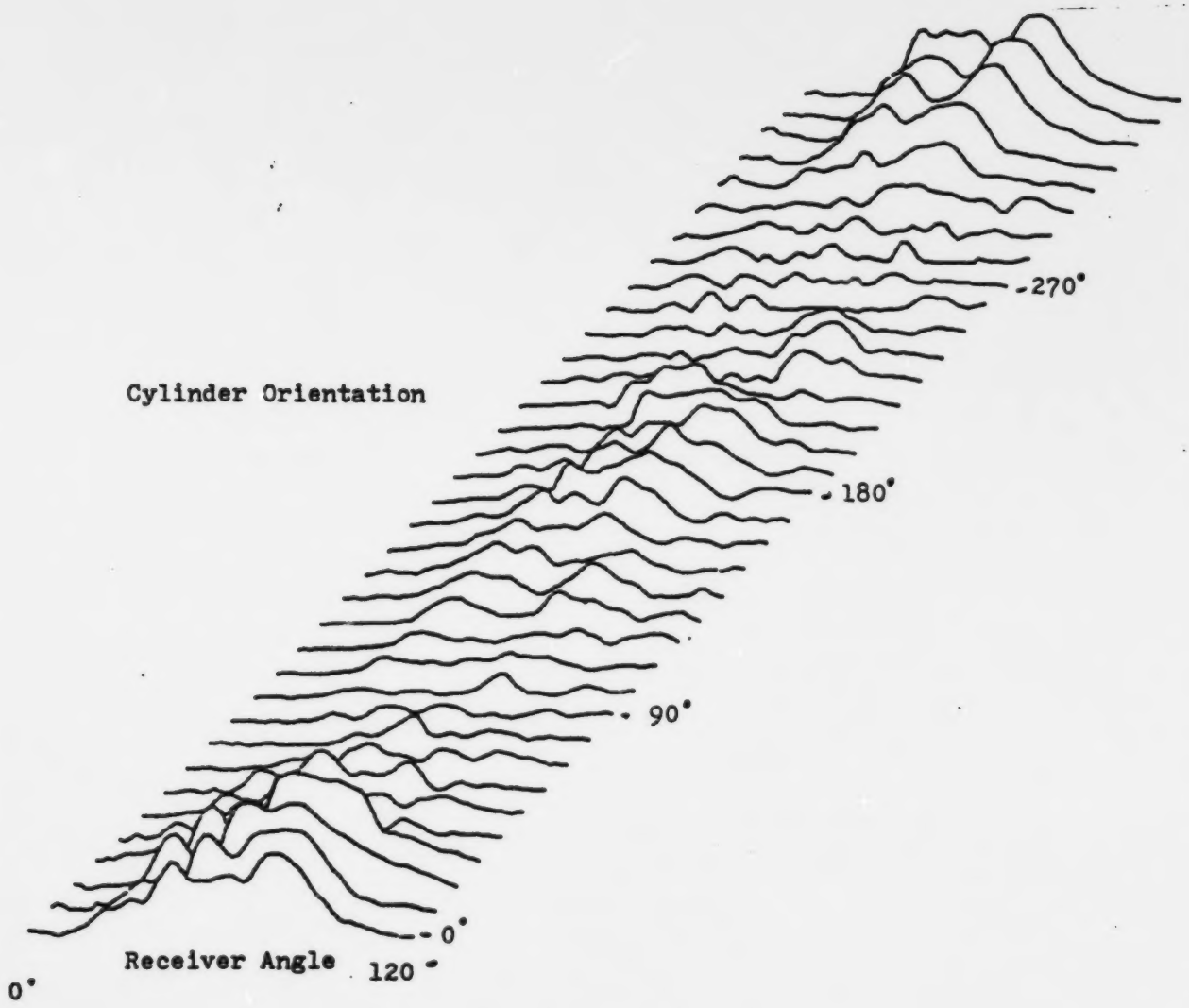


FIGURE 9c
TITANIUM GRADE 12 HT

170647 RD

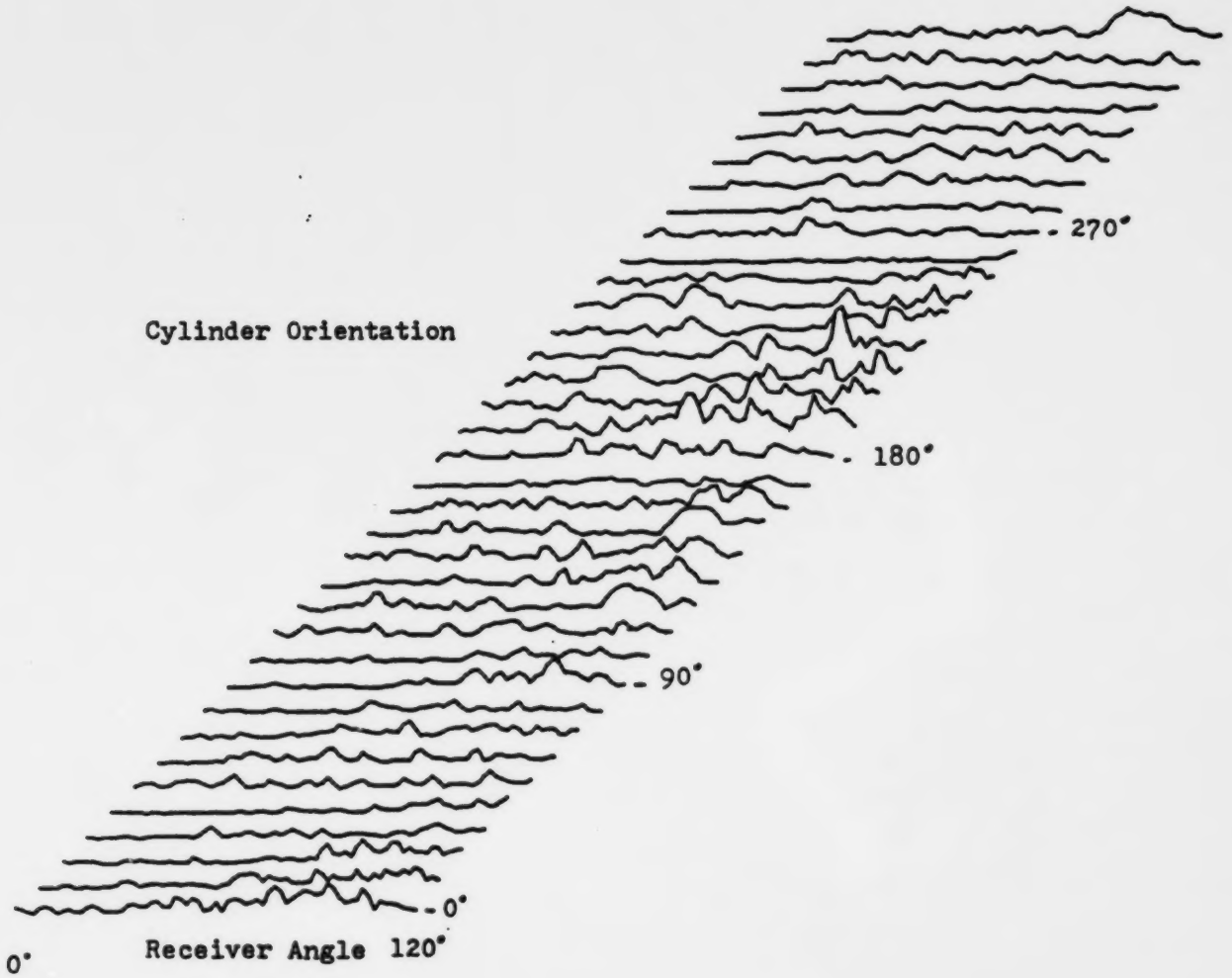


FIGURE 9d
HASTELLOY HT